585

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G. TAMBA TENGBEH T.E.C.(N.T.C); T.C Distinction (M.M.T.C);
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THE EFFECT OF GRASS COVER ON BANK EROSION

Supervisor: Prof. R. P. C. Morgan

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ABSTRACT

The effects of shoot and root densities of a grass vegetation on the erosion of channel banks through scour and slumping are assessed for a clay and sandy clay loam soil. By means of the tractive force approach, the effects of the vegetation parameters on scour were examined in a series of laboratory flume experiments using vegetated and bare root-free and root-permeated soils. For the bare (root-free and root-permeated) soils, the flows used varied from very shallow minimum depths of about 3 mm flowing at 0.7 m/s to 30 mm depths at 1.3 m/s. For the vegetated samples, flows ranged from about 10 mm at 0.3 m/s to depths of about 90 mm flowing at 1 m/s; all flows were at a constant flume channel bed slope of 2^o. Slump stability was determined for measured soil and geometric properties of a small channel, by computing changes in the factors of safety for varying effects of root density on the undrained torsional box shear strength, using the total stress equilibrium stability method based on Janbu's (1954) generalised procedure of slices. Additionally, experiments were conducted to determine the effects of increasing root densities on torsional box shear strength parameters, and on vane shear strength variations with soil drying from saturation.

The vane shear strength - moisture content relationships indicated that roots do not affect the established pattern of exponential increases in shear strength with soil drying between saturation and plastic limit. However, increases in root density increased the magnitude of shear strength at all moisture contents; at saturation, the increase is linear whilst at the plastic limit it is logarithmic. In all cases, roots increased the shear strength of the clay soils much more than the sandy clay loam soils.

The effect of root density on soil shear strength parameters showed that grass roots increase both the cohesion and friction of sandy clay loam soils by almost equal amounts, whilst mainly increasing only the cohesion of the clay soil. For the clay soil with very low root densities, dry bulk density was found to increase with increase in root density but for soils with high root densities, dry bulk density values decrease with increasing root density.

The scour experiments on the bare root-free and root-permeated soils indicated that for each soil, critical tractive force (CTF) linearly increases with both root density and vane shear strength. However, for both soils, CTF was mainly related to vane shear strength, indicating the potential importance of soil shear strength as an index of scour erodibility of cohesive channel bank materials.

The analysis of the relative effects of the grass vegetation parameters on scour resistance confirmed the dominance of vegetation shoots relative to the roots in resisting scour in non-bending vegetation. The results showed that it is the initial introduction of vegetation into bare (root-free) bank conditions that produces the greatest increase in scour resistance and that subsequent increases in vegetation density bring about relatively lower increases in scour resistance. However, in all the vegetation densities studied, root-permeated soils contributed significantly to scour resistance in low flows especially through low vegetation densities. Compared to root-free soil conditions, sandy clay loam soils permeated with 1.8 g/cm^3 of roots increased their scour resistance by more than 400%. Althgouh these results may only be indicative of the low flow depths as would exist in shallow grassed channels commonly used for agricultural run-off drainage, they nevertheless highlight the importance of root density in contributing to the total flow resistance of grassed channel banks.

The bank stability analysis indicated that for low channel banks (1.5m high), grass roots can stabilise banks with even vertical slopes against toe and slope vailures.

For high (2.25m) and vertical bank conditions, the results indicate that the effects of increases in root density may need to be complemented by bank shaping in order to achieve stability. The scour and bank stability findings indicate that the three most important characteristics for the selection of grass vegetation for bank protection are quick establishment, the development of a stiff shoot system and a strong root mat.

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DEDICATION

THIS THESIS IS DEDICATED TO MY BELOVED AGATHA

AND OUR SONS SAHR, TAMBA AND FAYIA.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Contimued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES AND PLATES

LIST OF FIGURES AND PLATES (Continued)

LIST OF APPENDICES

CHAPTER ONE

THE EFFECTS OF VEGETATION ON CHANNEL BANK EROSION

INTRODUCTION

1.1 Background

The erosion of streambanks is a continuous problem on perennial streams although it may vary in intensity throughout the year. On intermittent streams, bank erosion can also be a problem when flood water flows down the stream channel.

Stream channels vary so widely in geometry, material composition and ecology that any two are seldom alike (Keown et al, 1977). Nevertheless, in cross-section, a stream is limited by the extent of its banks. The bank extends from its base where it meets the bed of the channel, to its summit which is over-topped during floods. In this cross-section all colonies of plants which grow on the sides of the banks are usually termed "riparial vegetation" (Siebert, 1968).

A very important role of riparial vegetation is to protect the c hannel banks against erosion damage. Because the whole bank is not always uniformly submerged, the riparial vegetation commonly shows a zonation which is related to its tolerance to different degrees and duration of submergence over time. Four zones are identified using the dominant vegetation types as the naming criteria (Siebert, 1968). These are:

i. The zone of aquatic plants, which are permanently submerged;

ii. The reed-bank zone, with its lower part only submerged for about half the year, and composed of grasses;

iii. The softwood zone, which is only flooded during average high water periods and composed mainly of shrubs; and

iv. The hardwood zone, which is only flooded during periods of very high flows and usually composed mainly of trees.

Not all of these divisions may be present on all channel banks at all times. Nevertheless, the fact that riparial vegetation can exist at all these bank locations is important to this study because it does indicate that the whole bank of even perennial streams can be vegetated. Hence an understanding of how and to what extent vegetation in general protects bank materials from erosion damage is important if we are to successfully exploit them in streambank protection.

1.2 Statement of the Problem

Streambank erosion is a common occurrence along many channels in many countries (Barnes, 1968; Bowie, 1982; Dickinson and Scott, 1979; Lawler, 1986). In terms of area affected, bank erosion may be regarded as a small problem but when other related factors such as loss of life, the economic costs of sediment pollution of streams and harbours and damage to valuable land and engineering structures are considered, its significance greatly increases (Grissinger and Bowie, 1984). Apart from its fluvio-geomorphological importance (Hooke, 1979; Lawler, 1986; Thorne and Lewin, 1979), bank erosion is often considered as a significant and dominant source of sediment yield from many catchments (Barnes, 1968; Bowie, 1982; Cooke and Doornkamp, 1974, Garrad and Hey, 1989). The eroded sediment directly pollutes the streams and reduces their capacities as well as the capacities of engineering structures such as dams and reservoirs. This usually leads to floods which, in turn, may lead to loss of high value agricultural lands and property, damage to engineering structures and even to loss of lives (Barnes, 1968; Bowie, 1982; Grissinger and Bowie, 1984). Land that is subject to hillslope erosion may only be partly lost but land that is lost to bank erosion is completely and irretrievably lost. Also, bank erosion can lead to the undermining and collapse of roads and bridges with much more serious economic consequences than the value of the lost land (Grissinger et al, 1981; Hooke, 1979).

Where some of these effects have been studied and documented, the findings are instructive. Barnes (1968) estimated that in the United States (U.S.), there are about 483,000 Km of eroding streambanks producing about 450 billion Kg. of sediment each year. Bowie (1982) has also estimated that sediment yield from bank erosion from a watershed in northern Mississippi is over 1m Kg/Km each year.

Therefore, bank erosion can be regarded as an expensive process to tolerate. For instance, Grissinger and Bowie (1984) referred to an interim report by the U.S. Army Corps of Engineers (1978), which estimated the total damages by streambank erosion to be $ 270m per year. Barnes (1968) estimated that loss of land adjacent to stream channels is valued at about $ 11m annually. Costs of repairs are equally high. Barnes (1968) also estimated that removal of sediment from stream channels, harbours and reservoirs in the U.S. cost about $ 250m a year whilst, in the interim report cited above (1978), remedial works on damaged banks using conventional methods were estimated to cost $ 870 m per year. As urban areas and public facilities increase along waterways, the effects of eroding channel banks will become even more intolerable.

Over the years, various methods of strengthening/protecting channel banks have evolved successively. The most common of these methods has relied on the use of materials such as masonry, concrete, wood and even metal (Siebert, 1968). Some common forms of protective structures include rip raps, gabions, metal sheet piling and concrete structures of every type (Bache and MacAskill, 1984; Gray and Leiser, 1982; Hudson, 1986; Siebert, 1968). Although these methods are generally believed to ensure satisfactory protection of banks, Turnbull et al (1966) have shown that this may not always be the case. In their study of the erosion of the banks of the lower Mississippi which have been revetted with flexible concrete mattresses, they conclude that the revetments are causing "... the thalweg to deepen to a greater extent than if the banks were not revetted."

In any case, the use of these structures has been known not only to reduce the aesthetic value of the channels but also to hamper the establishment of riparial plant life (Siebert, 1968). These methods are also prohibitively expensive to install and maintain and, without constant upkeep, they are exposed to progressive deterioration by natural agents. So less expensive, more aesthetic but more or equally effective methods need considering.

The use of vegetation for bank erosion control has therefore been advocated because it is known to be effective, more reliable, cheaper and more lasting than structural control methods (Bache and MacAskill, 1981, 1984; Gray and Leiser, 1982; Grissinger and Bowie, 1984; Siebert, 1968). According to Keown et al (1977), "Of all the bank protection methods, vegetation is the only self-renewable method and, in many cases, the most economical and aesthetically pleasing". Although the role of vegetation in stabilising small agricultural runoff conveyance systems and streambanks has been recognised (Barnes, 1968; Bowie, 1982; Porter and Silberberger, 1960; Ree and Palmer, 1949), the relationship between cover and scour remains ill-defined (Bache and MacAskill, 1981, 1984). Studies on the influence of vegetation on channel scour have been directed mainly towards the interactions of the flow with the shoot system of vegetated channels (Ree, 1949; Ree and Palmer, 1949). The influence of roots on the flow and the strength of the channel materials have not been specifically considered in these studies. It is therefore not known, for instance, whether the roots contribute to protecting the soils by retarding erosive flows through vegetation. It is also not known how the effect of the roots on the shear strength of the materials influences the flow retardance of the soil.

Many studies have recently indicated that roots contribute to the shear strength of soils and to the stability of hillslope materials (Endo and Tsuruta, 1968; Waldron, 1977; Wu et al, 1979). Such studies have been concerned mainly with the effects of shrubs and tree roots. Trees growing in bank materials can have both stabilising influences - root-reinforcement, soil moisture modification and buttressing - and destabilising influences - root-wedging, wind throwing, weight of trees, surcharge and soil moisture modification (Bache and MacAskill, 1984; De Ploey, 1981b; Gray and Leiser, 1982). Although Brown and Sheu (1975) have presented a theoretical framework for analysing these destabilising effects, the relative magnitudes of these influences are not known. Therefore, it cannot be said with certainty that, on balance, trees on banks will not destabilise bank slope material. Grasses, however, do not seem to have such destabilising effects and so their exploitation for stabilising streambanks may therefore be a more desirable option (Siebert, 1968).

1.3 Objectives of Study

This thesis examines the potential role of grasses in protecting and stabilising bank materials by establishing how vegetation parameters influence bank erosion processes. Providing quantitative experimental evidence in this way is a vital first step towards successful modelling of the total effects of vegetation on streambank erosion.

The approach is to investigate the effects of the shoots and the roots of grass vegetation on the stability of two channel bank materials, a sandy clay loam and a clay, in terms of their resistance to scouring and slumping. An attempt is made to quantify the following:

i. The relationships between the vane shearing strength and moisture content of the soils at different rooting densities;

ii. The relationships between the torsional box shearing strength parameters of cohesion and friction, and rooting densities at soil zero matric potential;

iii. The relationships between vegetation shoot density, flow hydraulics and scour resistance;

iv. The relationships between rooting density, flow hydraulics and scour resistance; and

v. The effect of shear strength increases contributed by grass roots on channel bank stability against slumping.

CHAPTER TWO

RIVER BANK EROSION: PROCESSES AND CONTROLLING FACTORS

This study involves an evaluation of the effects of grass vegetation roots and shoots on shear strength and tractive resistance of some bank materials and a determination of how the resistance parameters are related to scouring and slumping. Before setting up experiments to study these effects, it is helpful to review our knowledge of the processes of bank erosion and their controlling factors, not only to highlight what is known already but also to identify those areas where more understanding is needed through further research. The review will therefore identify the gaps in our knowledge which this thesis will, in part, attempt to fill.

2.1 Bank Erosion Processes

Bank erosion is here defined simply as the removal and transportation of bank slope materials. The erosion of banks can be effected by one or, more commonly, a combination of processes. Turnbull et al (1966) working at two bank erosion sites on the Lower Mississippi recognised the occurrence of scouring and slumping as processes of erosion; they observed that all the slumping of the upper bank slope materials was initiated by the scouring of the lower banks by the flowing water. Lawler (1986) also observed that at one of his six sites of bank erosion measurement (PI/1), where the bank was much higher and the material more cohesive than at other sites, "... most bank erosion appeared to be achieved by fluvial undercutting followed by the collapse of overhanging peds or blocks." Neller (1988) observed that at knickpoint scarps in channels, the dominant mode of bank erosion was collapse as a result of undercutting during and immediately after streamflow whilst at other parts of the channels, erosion was mainly by fluid drag during storm events; throughflow was not observed to be an important bank erosion process. Although Hooke (1979) observed both

both scour and slumping, she found that scour was not related to the occurrence of slumping but rather, each process seemed to occur independently under different bank and flow conditions. She concluded that "Two main processes of bank erosion have been identified, direct corrosion and slumping. The former appears to be more directly controlled by river flow conditions and the latter mainly by soil moisture conditions."

Thorne and Lewin (1979) and Thorne and Tovey (1981) observed fluvial undercutting of the lower banks and the mechanical failures of the adjacent upper banks along streams with composite bank materials. Although they seem to accept that the upper bank failures were precipitated by the failures of the adjacent lower banks, they nevertheless state that ".. the failures of the upper bank were derived internally, and that consequently, they were not directly associated with the application of fluid stresses or fluvial processes per se." In all these studies, scour was observed to dominate the lower banks whilst slumping dominated the upper banks.

In other studies, however, one erosion process is usually regarded as more important than the others in eroding streambanks. Wolman (1959) considered the action of high flows as the most important significant factor in promoting erosion of the streambanks of the river Watts in Maryland. Knighton (1973) also determined, from 12 bank sites along five lengths of the river Bollin-Dean in Cheshire, England, that the action of high and moderate flows accounted for 70% of the total bank erosion whilst frost action and slumping effected only a small amount of erosion. He adds that "Material was sheared off by the flow and did not simply fail and collapse." In a study of the effects of four flood events on the river Patuxent in Maryland, Gupta and Fox (1974) recognised both scouring and slumping, and also the role of scour in promoting slumping but concluded that channel widening by scour of banks appeared to be the most important effect.

Hudson (1986) also observed that ".. the main damaging action is the scour of the river flow undermining the banks and causing their collapse" and concluded that "...most damage therefore results from scour by streamflow." However, Burgi and Karaki (1971) in investigating the role of outflow seepage in bank erosion concluded that at low channel flow velocities (<0.3 m/s) the erosion of the banks is due primarily to outflow seepage whilst at higher velocities the erosion process is dominated by the channel flow velocity. Because their observations were made from experiments involving well graded sands, the results, although instructive, cannot be applied to earth slopes. Hence the role of outflow seepage on the erosion of cohesive banks is not well understood.

Not all investigators consider scour as the most important bank erosion process. Lawry (1971) holds the view that "Gravitational mass movements of bank materials are probably the most effective and commonly the dominant mechanisms of stream bank recession." His observation was based mainly on a literature survey of geologically preserved and current bank failures. Little et al (1982) think that scouring of the toe and basal slopes in creating bank instabilities may lead to mass failures of oversteepened or overheightened banks but that "Fluvial erosion by detachment of intact in situ material from the bank surface does not seem to contribute significantly to bank retreat."

It seems agreed therefore that the two main bank erosion processes are scour caused by the drag force of the flowing water and mass movements caused by gravity failures. Bank erosion by outflow seepage, although not yet clearly understood, is rarely considered. Both scour and mass failure can occur independently at different bank sites. Where both processes occur at the same site, scour of the lower banks can cause instabilities of the adjacent upper banks which leads to their failure. However this type of failure may not be directly associated with the application of fluid stresses. On the other hand, there does not seem to be any agreement about the relative importance of scour and mass failure in eroding streambanks. This seems to be due to the differences in the manitudes of the heights and probably angles of the channel banks studied. The channel banks studied by both Knighton (1973) and Wolman (1959), who observed scour to be the most important, were between 0.75 and 1.5 m high whilst Gupta and Fox (1974) and Lawry (1971) studied banks 2.7 to 10 m high. It would seem therefore that slumping is likely to predominate over scour on high and probably steep banks whilst scouring would predominate on relatively low channel banks especially if they have gentle slopes. Since this study is concerned with the erosion of cohesive bank materials, the main forces acting to cause scour and slumping of cohesive channel banks are represented in Figure 2.1.

2.2 Scour Erosion.

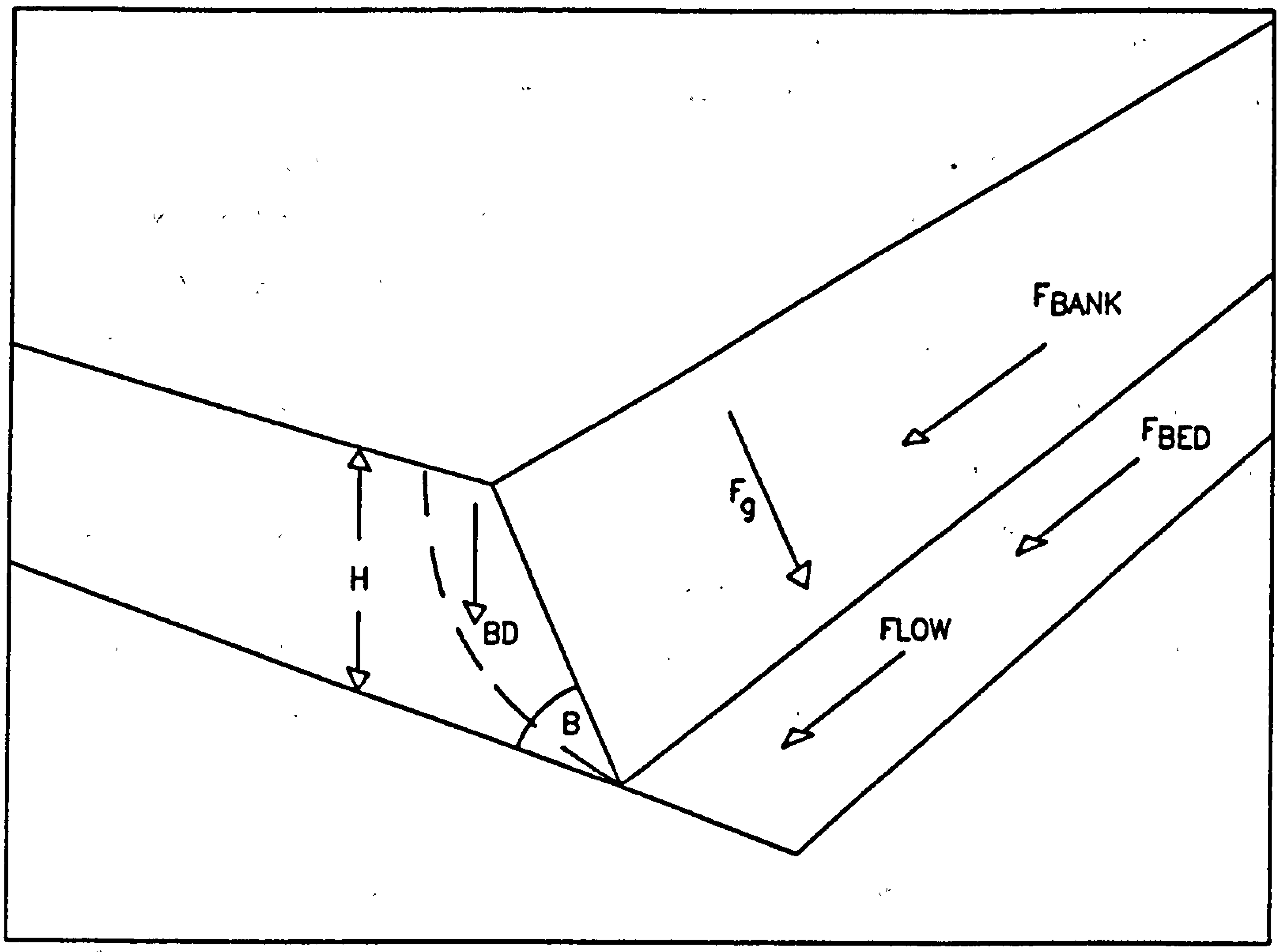
Scour refers to the enlargement of a flow section by the removal of surface material comprising the boundary of the channel through the shearing action of the flowing water (Laursen, 1953; Lane, 1955). Implied in this definition is the fact that the flowing water exerts forces on the particles of the material comprising the channel and causes their movement. Whether or not a channel bank material erodes by scour, therefore, depends upon the interaction between the energy or power of the flowing water and the resistance of the bank material.

2.3 Scour Forces

Erosion by scour depends on the magnitude of the velocity or the tractive force of the flowing water (Chow, 1959). These two factors have been used in many investigations into channel scour especially as a basis for stable channel designs.

2.3.1 Flow Velocity

Several studies on scour erosion have been based on velocity; these studies are discussed in ASCE (1963), Chow (1959) and Graf (1971). One problem associated with the use of velocity as a scour criterion is the accurate determination of the bottom



KEY: F_{BED} = Flow Force on channel Bed; F_{BANK} = Flow force on channel bank;*F_g = gravity force acting on bank; H = bank height; B = bank slope; BD = Bulk density (unit weight) of soil; ---- = assumed failure plane.

FIGURE 2.1 DEFINITION DIAGRAM OF THE MAIN COMPONENTS OF FLOW FORCES IN A CHANNEL BANK AND OF BANK PARAMETERS FOR STABILITY ANALYSIS

*Note that for cohesionless materials on the bank of a channel in which water is flowing, two forces act at right angles to each other; the flow force in the direction of the flow and the gravity force component which tends to cause the particles to roll/slide down the slope of the bank. But "For cohesive and fine noncohesive materials the cohesive forces, even with comparatively clear water, become so great in proportion to the gravity force component causing the particle to roll down that the gravity force can safely be neglected." (Chow, 1959; Page 171).

velocity acting on the soil particles. This problem is usually overcome by using the surface or the average velocity values of the flow. Secondly, the critical velocity for the initiation of motion is highly dependent on the size, shape and density characteristics of the particles composing the channel. Hjulstrom (1935) determined critical velocities at which materials of given grain sizes eroded. This study, although undertaken for materials of uniform grain size, showed that the effect of flow velocity is complexely related to particle size variation. For soils with grains larger than about 0.5mm (coarse sand, pebbles and cobbles), the critical erosion velocity for particle movement increases with particle size whilst for grains smaller than 0.5mm (fine sand, silt and clay), the critical velocity increases with decreasing grain size. Other investigations associated with specific model studies were similarly undertaken but using cohesive materials. For instance the Tennessee Valley Authority (TVA) (1953 and 1960) performed verification tests in flumes in Fontana and Fort Henry (U.S.) respectively, as a basis for selecting suitable bed materials that would not erode under certain flow velocities; Straub (1945) used undisturbed field samples to determine the flow velocities at which serious erosion was first observed (Moore and Masch, 1962).

Similar studies, but concerned mainly with stable channel designs, determined the mean maximum velocities to which different soils could be subjected for a reasonable length of time without scouring. These velocities, more commonly referred to as permissible velocities, are variously called Safe, Limiting, Allowable or Non-eroding velocities (Lane, 1955). According to Chow (1959), Etcheverry (1915) published probably the first table of maximum velocities that are safe against scour erosion; his data were not, however, related to channel size nor to specified channel geometries (Lane, 1955). By the continuity relation for uniform channel flow (Webber, 1971), for a given discharge, velocity will vary depending on the cross-sectional area of the channel; consequently, larger channels are known to tolerate larger permissible velocities than smaller channels (Chow, 1959; Lane, 1955). When Fortier and Scobey (1926) published their permissible canal velocities, based on information collated and analysed from various practising hydraulic engineers, they recognised this problem of channel geometry and therefore specified flow depths of 1m or less for their permissible velocity values and suggested a correction factor for greater depths of flow. Lane (1955) and Chow (1959) have summarised these values and those from a Russian Source (1936) for various kinds of soils. The wide range of permissible velocities from these sources clearly indicates their relationship with the resistance of channel bank materials.

Perhaps the most comprehensive work using permissible velocity in scour erosion is that undertaken by the United States Soil Conservation Service (Ree, 1949; Ree and Palmer, 1949). The results of these studies also show that for the channel material used, velocity is related to channel size and bed slope. Although the permissible velocity values from these studies are widely used as a basis for the design of conveyance channels that can be stable against scour, it is recognised that they cannot be directly applied to channels constructed in materials other than those for which they were developed (Ree and Palmer, 1949).

From this review, it is clear that in a channel, flow velocity is very complexely related not only to the soil properties of the channel boundary, but also to the geometric properties of the channel. The use of flow velocity as a factor of scour erosion would therefore require the tabulation of permissible velocities for each possible combination of channel geometry and soil properties. It is not therefore surprising that Lane (1955) observed that as velocity is not a completely rational parapeter for determining scour, permissible velocity data are not entirely satisfactory in studying scour in channels. Hence reaching a satisfactory analysis of scour erosion from a study of the velocities acting on the channel boundary materials has not been feasible (Lane, 1955; Temple, 1980). Consequently, the use of the bottom shear stress or tractive force as a more satisfactory scour criterion has been widely accepted in hydraulics by many workers (Chow, 1959; Lane, 1953; Graf, 1971).

2.3.2 Tractive Force

Tractive force, which is also known as shear or drag force, is the force which is exerted on the boundary of the channels by the motion of the water (Lane, 1955). The concept of tractive force is believed to have been introduced into hydraulic literature by Du Boys in 1879 (Chow, 1959; Lane, 1955). The force acts in the direction of flow (Figure 2.1). It is not the force on a single particle but the drag force exerted over a certain area of the channel boundary. Consider a body of flowing water in a channel section of length, L, with the depth of flow being D, and the wetted perimeter being P. (Figure 2.2). Since the flow in an open channel is mainly influenced by friction along its boundaries, ignoring air friction, the frictional effect on the flow may be measured by the tractive forces (TF) along the boundaries. Using the principles of fluid dynamics (Chow, 1959), the surface of contact of the flow with the channel boundary is equal to the product of the wetted perimeter and the length of the channel section considered, PL. The total force resisting the flow of the water in the channel reach is therefore equal to TF.PL, where TF is the average unit tractive force, parallel to the direction of flow within the body of water. This body of water of cross-sectional, A, has a weight component in the direction of flow of WALS where W is the unit weight of water and S is the bed slope. A basic principle of uniform flow which is believed to have been claimed by Brahms in 1754 (Chow, 1959, Thornes, 1980) states that the effective downstream component of the gravity force causing the flow (Figure 2.1) must be equal to the total force of resistance.

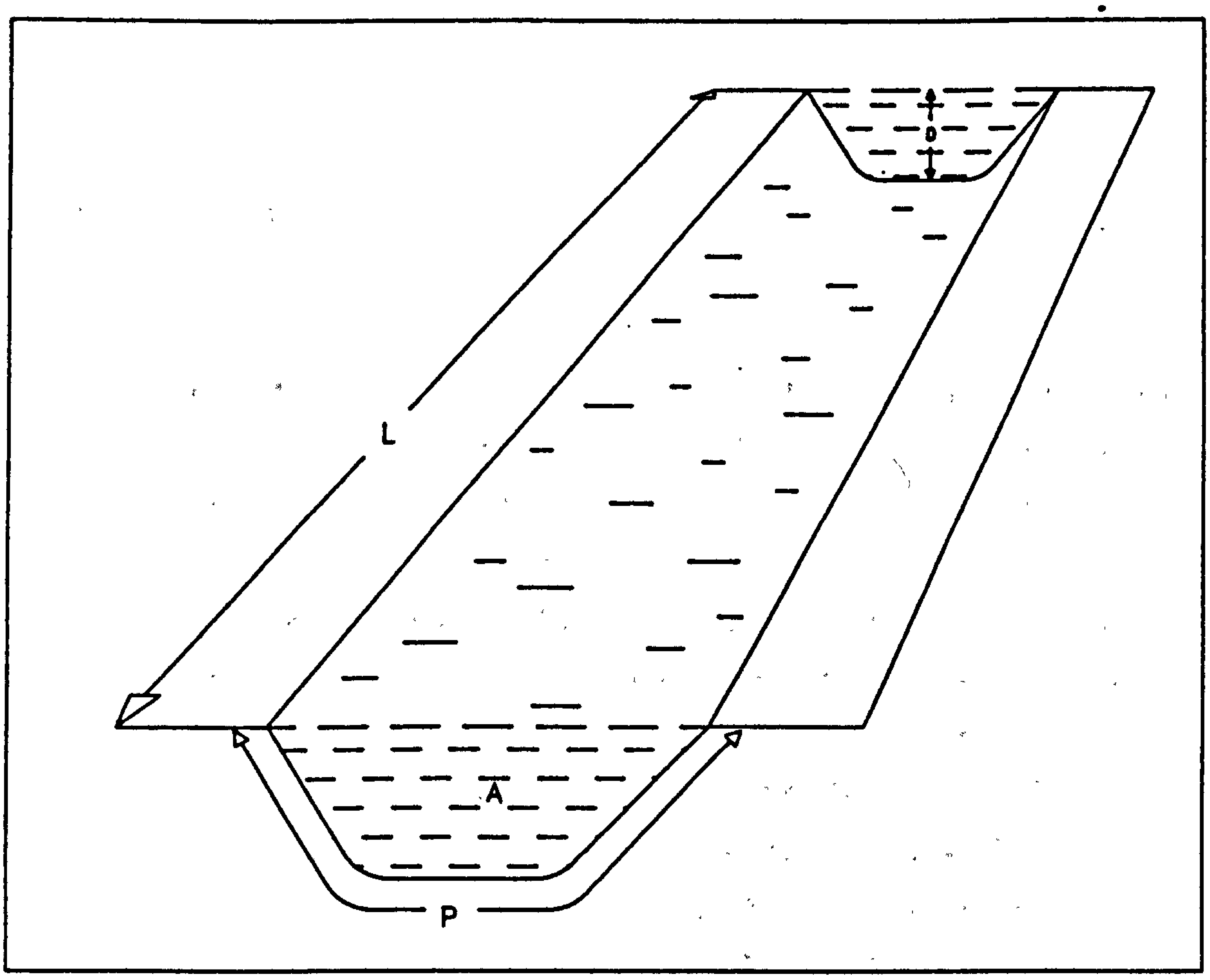
Hence,
$$TF.PL = WALS$$
$$TF = W\frac{AL}{PL}S = WRS \qquad (2.1)$$

Where

W = The unit weight of water (9810 N/m^3)

R = The hydraulic radius of the channel

S = The sine of the slope of the channel bed.



KEY: L = Length of channel Section;
D = Depth of Flow;
P = Wetted Perimeter;
A = Cross-Sectional area of flow.

FIGURE 2.2 DEFINITION DIAGRAM FOR THE DERIVATION OF UNIT BED TRACTIVE FORCE OF FLOW

In wide open channels and for rectangular channels with sheet-metal side-walls which are known to have negligible retarding effects on flow, the hydraulic radius, R, is equal to the depth of flow, D (Chow, 1959; Graf, 1971; Ree and Palmer, 1949). Hence the unit tractive force, which is about equal to the bed tractive force (Chow, 1959; Lane, 1953) becomes:

$$TF \quad = \quad WDS \qquad (2.2)$$

As was noted in Figure 2.1, for the cohesive soils used in this study, the tractive force could also be regarded as the main force component acting to cause scour on the banks without significant error. The tractive force at which the channel boundary material begins to erode is called the critical tractive force (Lane, 1953). The critical tractive force which a channel material can sustain without causing excessive scour is the permissible tractive force (Smerdon and Beasley, 1959). The tractive force theory, as opposed to the permissible velocity criterion which is empirical, is a theoretical relationship because it is derived strictly from knowledge of the forces that act on a free body of water which extends from the free surface to the channel bed (Chow, 1959; Lane, 1955; Smerdon and Beasley, 1959).

According to Lane (1955), although the available information strongly supported, by 1952, the preference for tractive force rather than velocity as a basis for studying scour erosion, there were no data available on limiting tractive forces for cohesive and non-cohesive soils. Lane (1955) therefore analysed the available data on permissible velocities (from Etcheverry (1915); Fortier and Scobey (1926) and the Russian Source (1936)) and determined the values of the tractive forces which they represented. Thus for channels in non-cohesive soils it was possible to relate the tractive force at which bed movement begins to the physical properties of the soil. However for channels in cohesive soils, the relationships between tractive force and soil movement were not as yet determined.

Since then, Einstein and Barbarossa (1952) have used the tractive force approach in studying frictional losses in river channels whilst Smerdon and Beasley (1959, 1961) have used it to determine the relationships between critical tractive force and selected cohesive soil properties. Others who have used the consept in studies of scour in cohesive soils include Dunn (1959), Flaxman (1963), Dickinson and Scott (1979), Grissinger et al (1981), and Temple (1980, 1982, 1983, 1985). All of these studies seem to indicate that the tractive force theory presents a logical criterion by which the problem of scour stability of open channels in cohesive soils can be investigated and that it offers a way to evaluate the shear at the interface between the flowing water and the channel material. Another advantage of this approach is that, if properly formulated, the tractive force, even in vegetated channels, is related only to the properties of the channel material (Temple, 1980, 1985). Since the pattern of tractive force distribution in channels is practically unaffected by the size of the channel section (Chow, 1959), it seems that the use of the tractive force approach greatly simplifies the investigation of scour erosion in cohesive channels.

This study is partly concerned with determining the permissible tractive forces for bare soil channels for which data are often reported in the literature for the root-free soil condition (Ree and Palmer, 1949; Chow, 1959; Webber, 1971). However this is not the soil condition occurring in vegetated channels because of the presence of roots within the soil matrix. This study is therefore amied at determining the permissible/critical tractive forces for the root-permeated bare soil conditions that would occur if all the grass vegetation were removed but the soil remained unaffected. As will be shown later (Section 2.6), hydraulic resistance values are also needed for this soil condition for studying scour in vegetated channels. This kind of information is not known to exist. Because the tractive force approach has the advantage of being related only to the properties of the soil boundary, it is used in this study to evaluate the effects of vegetation and root density on the scour stability of channel bank materials.

2.4 Erodibility of Bank Materials

In discussing the factors that influence the erodibility of channel bank materials, it is important to note that they cannot be compared with soils on agricultural lands. Agricultural soils are usually loose and non-coherent surface soils and their erodibility is controlled mainly by the character of the discrete particles or aggregates composing them (Bryan, 1976). A detailed review and assessment of various erodibility indices are presented by Bryan (1968) and (1976) respectively. Emphasis in this discussion is placed on the factors influencing the erodibility of the generally coherent and usually cohesive channel bank materials.

The erodibility of channel banks depends almost entirely on the inherent properties of the material composing them and how these properties are influenced by moisture related conditions (Grissinger et al, 1981; Lawler, 1986; Little et al, 1982; Morgan, 1986). These properties include their physical, mechanical and chemical characteristics (Flaxman, 1963; Grissinger, 1966; Keown et al, 1977; Nielson, 1973). The inherent soil factors that influence the scour erodibility of channel banks include variables such as: particle size, bulk density, organic matter, aggregate stability, friction, cohesion, atterberg limits, soil fabric, cation exchange capacity, cation type and concentration, pH and their interations. Roots and root growth have frequently not been considered as soil properties in erodibility studies probably because most of the other properties are determined in the laboratory for loose and root-free soils.

Because of the difficulty of considering this multiplicity of factors together, many workers have attempted only a limited analysis of them and shown that erodibility is related to only one or two. However, other investigators have either found no relationship between some of the above-listed properties and erodibility, or have found other properties to be also important. A possible reason for this appears to be that many investigators have tried to relate the erodibility properties of cohesive soils to the same variables as those which affect the erodibility of cohesionless materials. According to Grissinger and Asmussen (1963) and Nielson

(1973), erodibility of cohesionless soils depends upon properties such as particle size, specific gravity, density and surface texture of the individual particles whereas the resistance of cohesive soils to erosion is due not only to their physical and mechanical properties, but also, and probably mainly, to their electrochemical properties which are controlled mainly by the clay fraction. The erodibility of cohesive soils is thus much more complex and may not therefore be expected to be explained by the same variables or in the same way as the erodibility of cohesionless soils. However, this review will discuss some of the soil properties that have been related to erodibility with a view to determining which, if any, shows promise for use in this work.

2.4.1 Particle Size

Particle size has been an attractive area of research in cohesive soils because of the good correlation which has been obtained between fluvial erosion and particle size of coarse grained soils. However, although particle size may influence the erodibility of cohesive soils, other variables become important in the relationship. Dickinson and Scott (1979) and Grissinger et al (1981) have found percentage silt, and clay content, respectively, to be highly correlated to soil erodibility. However, Grissinger (1966) and the work of Liou (1970) as reported by Nielson (1973) have shown that the effect of particle size, especially clay content, is not always consistently reliable because the relationship depends upon properties such as the type, amount and orientation of the clay minerals involved. Dunn (1959) found tractive resistance to be related to percentage silt plus clay and to vane shear strength but observed that the amount of fines, which may originate from pulverised quartz grains for instance, can be a poor indication of the cohesiveness of the soil. Smerdon and Beasley (1959) found not only mean particle size and percentage clay, but also plasticity index and dispersion ratio to be related to the soil's resistance to erosion by flowing water. They observed that ".. all clays do not exhibit the same tendencies toward cohesion when present in the same amount. Therefore percentage clay alone would not be expected to indicate the cohesive properties of all soils." From this brief discussion, it would appear that particle size is not a reliable indicator of the erodibility of cohesive soils mainly because it depends on the type of clays involved.

2.4.2 Atterberg Limits

The plasticity index is defined as the numerical difference between the plastic limit and the liquid limit in Atterberg Limits soil tests. Chow (1959) reports that the U.S. Bureau of Reclamation has investigated the use of this index as a soil property that can be used to indicate resistance to scour for cohesive soils. The critical plasticity index value commonly used is 7, with scour occurring for moderate tractive forces below this value. However, scours were still observed in many cases where the index is above 7. Flaxman (1963), after examining a number of natural channels with respect to data on plasticity, found that soils of low plasticity or, in one or two cases, no plasticity, were exhibiting considerable resistance to erosion. Grissinger (1966) attempted a characterisation of some soil samples using the plasticity index as the sole criterion but was not successful because similar plasticity index values were obtained for all the samples. However, he found that the effect of antecedent water on stability was different for the same soil samples and so concluded that "...erroneous conclusions could be reached by depending solely upon plasticity index."

These conflicting findings would be expected because of the complex nature of the property of plasticity. It is a property that depends on the cohesiveness of the soil which is determined by the electrochemical properties of the clay minerals present. Because of this, soils generally exhibit plasticity when they contain an appreciable percentage of clay-sized particles. However, plasticity depends also on the type of clay mineral which contributes to most of the clay-sized fractions; the plasticity of montmorillonite is greater than that for illite which is greater than that of Kaolinite (Baver et al, 1972). In addition, plasticity of soils depends on the nature of the exchangeable cations and the organic matter content. These are particularly important as binding agents (Spoor and Godwin, 1979). It is known that different cations have different effects on the plasticity of a given clay while the same cation may have different effects on the plasticity of different clays (Baver et al, 1972). Because of the wide variation in the nature of the predominant exchangeable cations that can exist in soils, there can be a wide variation in the Atterberg limits between different samples of the same clay minerals (Baver et al, 1972). It can be seen therefore that the plasticity index of soil is so complexely dependent on many factors that, as a physical property, it may not, on its own, be a reliable indicator of the erodibility of cohesive soils.

2.4.3 Shear strength

The shear strength of soil is defined as the maximum resistance which a soil can offer under certain shear stress conditions before its particles start to slide over one another (Baver et al 1972; Nielson, 1973). The shear stresses can be those due to moving fluids, gravity or mechanical loads (Morgan, 1986). For a given soil, shear strength will vary mainly with moisture content and its temperature status.

2.4.4 The effect of moisture content on shear strength.

Shear strength variations with moisture content are important in understanding the behaviour of soil subjected to vertical or horizontal stresses under different soil moisture conditions. This understanding is important in studying the slump and scour stability of channel banks.

Nichols (1932) investigated the relationship between shear strength and moisture content for 7 soils at three compaction pressures; results were presented for three of these soils - two clays and a clay loam; shear was determined using a model tool. The results showed that shear strength increased with moisture loss up to a certain moisture content and then decreased. He found that the relationship of the rising and falling shear values with decreasing moisture content is linear for all the three soils. A similar linear shear strength - moisture content relationship is found for a clay, a clay loam and a sandy loam by Ohu et al (1986) using a shear vane device to measure shear strength. They, however, did not extend their strength determinations to the higher moisture content levels around the liquid limit; the strength behaviour of their soils at these moisture contents is therefore not known. Davies (1985) also found that for a rather restricted range of moisture contents well below the liquid limit, the shear strength of a heavy clay loam soil increased linearly as the moisture content decreased. A similar relationship is observed by Panwar and Siemens (1972) for a silty clay loam at three bulk densities using shear results from unconfined compression tests. Here again shear strength was only determined for intermediate moisture contents well below the liquid limit. Camp and Gill (1969) found that both the cohesional and frictional components of the shear strength of a silt, a silty clay loam and a clay soil, as determined by the triaxial method, linearly increased with decreasing moisture content. Panwar and Siemens (1972) also found this to be the case for a silty clay loam. In both studies, friction and cohesion were determined for moisture contents well below the liquid limit.

Although other studies have also found a general increase in soil shear strength with decreasing moisture content, they have not observed a linear trend in the relationship. Rather, there is general tendency for shear strength to increase gradually at first as soil dries out from a high moisture content state, and then to increase more rapidly as the soil dries out at intermediate moisture contents. This observed behaviour of soil has therefore produced a curvilinear trend in which shear strength exhibits an exponential increase with decreasing moisture contents. Bjerrum (1950) and Chorley (1959) observed this type of relationship for clay soils. Towner (1973) studied the shear strength - moisture content relationship for seven soils having a wide range of textures from loamy fine sand to clay, when he calibrated the fall-cone method of measuring shear strength against the unconfined shear strength method. He found that there was a logarithmic increase in shear strength with decrease in moisture content for all the soils studied. Spoor and Godwin (1979) found that a similar relationship characterised the behaviour of two clays and an unnamed alluvial gley soil. In all of these studies, soil strength behaviour was observed over a wider moisture content range than in the studies that observed a linear strength - moisture content relationship. It is therefore hypothesised, that for moisture contents varying from saturation to plastic limit, the shear strength - moisture content relationship is curvilinear whilst for moisture contents varying from below saturation, the relationship is linear.

The effects of freezing temperatures, especially when minimum air or ground temperatures are at or below freezing, on the shear strength and hence on the stability of slope material have been observed for some time. The main influence of freezing temperatures on shear strength is through frost heaving and needle ice crystal growth (Bullock et al, 1988; Kay et al, 1985; Lawler, 1986). The processes involve the expansion of water freezing within the soil thereby exerting high shear stresses which disrupt the soil. The ice crystals also lubricate shear planes and thus lower cohesion and inter-particle friction leading to material instability. These effects are more pronounced when freezing is preceded by bank material saturation because then the ice crystals grow larger and hence exert greater material-disruption forces (Bullock et al, 1988). Confirmation of this has come from studies of scour erosion of river banks in humid temperate environments. Knighton (1973) and Wolman (1959) both observed the role of frost action in enhancing the effectiveness with which river flows eroded banks. Lawler (1986) demonstrated statistically that frost activity dominated over other variables in explaining the observed erosion and maximum erosion rates of channel banks at all his measurement sites on the Middle Ilston river in Wales.

The shear strength-moisture content literature indicates two main soil shear strength behaviour patterns with loss of moisture content - the linear and the logarithmic. Precisely why the shear strength of these soils has been found to exhibit these apparently different behaviour patterns with loss of moisture content is not very clear. It is possible, however, that the differences in the range of moisture contents used in observing shear strength may partly explain the observed difference. It would appear also, that whether an increasing and decreasing shear strength with decreasing moisture content is observed, or only an increasing shear strength, depends mainly on whether the soil is being wetted or dried. Baver et al (1972) have shown that differences in soil preparation can lead to differences in shear strength change with moisture loss which are contradictory. They presented variations of cohesion, the main shear strength component in cohesive soils, with moisture for two samples from different studies. One sample was puddled whilst the other was a non-puddled sample that was wetted. The puddled sample exhibited a logarithmic increase in cohesion with loss of moisture throughout the moisture content range used. The non-puddled sample showed a logarithmic increase in cohesion with increase in moisture content from 5% to a peak at 15%, beyond which cohesion decreased with increase in moisture as in the puddled sample. The main difference in the behaviour of the two samples is that the puddled soils showed an increase in cohesion as the soil dried while the non-puddled soil showed a decrease. This was explained by the fact that puddling soils produces maximum contact between particles which in turn causes high cohesion due to interparticle attractions, whilst non-puddled soils that are wetted do not experience this effect.

All the shear strength - moisture content relationships commonly reported in the literature are for root-free soils. It is therefore not known what the shear strength - moisture content relationship is for root-permeated soils or for soils with different densities of roots. Such knowledge is important in erosion studies because in many situations, the soils are permeated with roots at different densities. Such knowledge should increase our understanding of how the matrix of roots, soil water and soil particles in root-permeated soils behaves when subjected to loss of moisture and whether the strength change in these soils differs from that of root-free soils.

2.4.5 Synthesis

From the evidence in the literature, it seems that the ultimate effect of the soil properties that are commonly related to soil erodibility is either to increase or decrease the inherent shear strength of soil. Chorley (1959) has reported that particle size and bulk density are related to shear strength variations with moisture content. Bulk density has also been directly related to shear strength by Al-Durrah and Bradford (1981); Camp and Gill (1969); Ohu et al (1986) and Taylor et al (1964). Flaxman (1963) has indicated that particle size, bulk density, permeability and plasticity index are each related to shear strength variations with moisture content. Lambe and Whitman (1969) have pointed out that perhaps the most important contribution which soil composition has to make in erosion is through its influence on sediment strength. Organic matter has been shown to either increase or decrease shear strength depending on whether it increases or decreases bulk density (Adams, 1973; Davies, 1985; Ekwue, 1987). Variations in the electrochemical properties of soils have been shown to either increase or decrease shear strength. In studies by Liou (1970), as reported by Nielson, (1973), the shear strength of cohesive soils has been related to temperature, orientation of clay minerals (fabric), cation type and concentration and pH.

Plant roots are known to influence the shear strength of soils in two main ways. During their growth roots exude organic substances which increase the stability of soil aggregates by their binding effect (Reid and Goss, 1980, 1981). The density of roots reinforces the soil and thereby increases its shear strength (Endo and Tsuruta, 1968; Waldron, 1977; Wu et al, 1979).

From this evidence in the literature, it is proposed that, for a given soil, shear strength is a good indicator of its erodibility because it embraces the effects of all the other soil properties. Nielson (1973) expressed a similar view when he said that in a given soil, the erosion resistance should be related to its shear strength. Al-Durrah and Bradford (1981, 1982), Cruse and Larson (1977), Rauws and Govers (1988) and Schultz et al (1985) have all supported this view recently.

2.5 The use of Shear Strength in Erosion Studies

Shear strength has been little used in the past in soil erosion studies (Morgan, 1986); but recent literature tends to support the use of shear strength to determine the erodibility of soil. Chorley (1959) is probably the first to suggest the use of shear strength in an index of erodibility. In his study of the geomorphological significance of some Oxford soils, he argued that from the point of view of erosion in a soil covered region, it is the stress necessary to shear off the surface soil particles which is significant. His index has never been fully tested because of limitations in the shear strength measurement technique employed. As Bryan (1976) argued, Chorley's (1959) estimation of shear strength by a Vicksburg penetrometer is dubious because the penetrometer actually measures compactability rather than shear strength and because the penetrometer measurement was made normal to the soil surface whilst shear stress is exerted by flowing water parallel to the surface. Bryan (1976) nevertheless maintained that in the study of hillslope geomorphology, the soils involved are usually coherent and therefore entrainment resistance is governed by shear strength. He therefore advocated giving greater attention to the use of shear strength in erosion studies.

Flaxman (1963) concluded that the erosion resistance of cohesive soils can be determined by the unconfined compressive strength of saturated undisturbed soils. He determined, from regression analysis, that although permeability, particle size, bulk density and plasticity index were significantly related to shear strength, there was little consistency in any one of these variables in explaining shear strength variations in the 28 soils tested. He found, for instance, that although permeability was related to shear strength for most of the soils, there were some samples that were nearly impermeable but had no resistance to erosion. He also found that for a certain strength, plasticity was important whilst for another strength, density and particle size were important.

These findings strongly support the view that it is the combination of soil variables that explain observed variations in shear strength and that the use of only one or a few of them on their own may not. This seems to indicate that the undisturbed soil embodies certain characteristics pertaining to shear strength that are not easily separated into component parts in predicting a soil's erodibility. It would therefore seem reasonable to propose that shear strength would be a better indicator of the scour erodibility of soil than many of the individual properties of soil hitherto used.

2.5.1 The use of shear strength in rainfall erosion studies

Recently, shear strength has been increasingly used as a basis for predicting the detachability of soil by raindrop impact and also for predicting rill and interrill erosion. Rauws and Govers (1988) have found that overland flow incision of beds of loose sediments and cohesive soil material is related to the shear strength of the soil. Watson and Laflen (1986) studied the interrill erodibility of three soils using a rainfall simulator and "...found that field measurements of soil strength could be used to obtain information needed for predicting interrill soil erosion."

They found that vane strength was better for predicting interrill erosion than compressive strength. This was probably because interrill erosion is more of a shearing rather than a compressive process of deformation. Cruse and Larson (1977) found that soil splash rate increases exponentially as the unconfined compression shear strength decreases. Shear strength was measured by an Instron Universal Testing machine. They estimated that shear strength explained about 80% of the observed variation in soil splash. Al-Durrah and Bradford (1981, 1982) and Schultz et al (1985) also found a similar relationship between shear strength, measured by the fall cone method, and splash rate. Al-Durrah and Bradford (1982) found that soil properties other than shear strength predicted only about 60% of splash variations whilst shear strength alone predicted 81% of splash variations for all nine soils tested and between 88% and 97% for individual soils. From the results obtained, they concluded that shear strength is a better predictor of soil detachment by raindrop impact than other plysical or chemical properties of the soils. This is because shear strength is closely related to the actual forces associated with a soil's resistance to erosion.

2.5.2 <u>The use of shear strength in scour erosion studies</u>

In studies of erosion by flowing water in open channels, some investigators have related shear stress (tractive force) either directly to shear strength or to properties that are known to be affected by the shear strength of soil.

According to Partheniades (1965), Sunborg (1956) found a linear relationship between the cohesive strength of the bed material and the critical shear stress on the bed surface.

Dunn (1959) also found that critical shear stress linearly increased with vane shear strength. On the other hand, Partheniades (1965, 1972) found that scouring shear stresses and the erosion rates are independent of the strength of the bed material. It is however difficult to compare his results with Dunn's, mainly because of significant differences in the salinity of the eroding media and in the methods of sample preparation and shear strength measurement. Dunn (1959) prepared all his samples in the same way and apparently used non-saline water. Partheniades (1965) used a penetration device which is more likely to measure compactability rather than shear strength (Bryan, 1976). Also, the three bed samples tested were prepared differently. One bed was "made of natural material at field moisture. The second was a flocculated deposited loose bed..." and the third was prepared by completely remoulding and compacting/levelling the first bed. All samples were tested in water at ocean salinity. The effect of the high salt concentration in the eroding water is to produce a lower shear stress because of dispersal of the clay particles (Liou, 1970). It is not clear, however, how this dispersal would be affected by the compacted and remoulded or levelled beds, but as Altschaeffl (1963) points out, the erosion of clay can be severe regardless of the state of soil compaction, if the proper fluid environment is present. As Partheniades' tests were conducted with water at ocean salinity, the influence of the eroding water on the erosion of the samples cannot be determined.

Flaxman (1963) found a positive linear correlation between tractive power (an adaptation of tractive force) and unconfined compression strength of saturated undisturbed cohesive soils in channels. According to Nielson (1973), Bergharger and Ladd (1964) found that compression strength has no effect on erosion. Nielson (1973) suggests that differences in sample preparation methods may have been the reason for the difference between Flaxman's and Bergharger and Ladd's findings. The ASCE Task Committee on Cohesive Soils (1968) presented positive linear correlations between critical shear stress and vane strength for five different soils. The only soil which showed an opposite trend is the San Saba clay but no explanation is given for this.

Smerdon and Beasley (1959) found the critical tractive force of flowing water in a flume to be correlated with plasticity index, dispersion ratio, percentage clay and mean particle size. They observed that the correlations with the first two variables are more reliable because these measure cohesion, and hence shear strength, more directly, whilst the others are an indirect index of cohesion. However, all these properties have been shown to be related to the shear strength of soil. Grissinger (1966) has similarly related the stability of cohesive materials against the erosive force of flowing water in a flume to properties that are related to the shear strength of soil. Other known studies which have used cohesion as the main shear strength factor in erosion by flowing water include the TVA Fontana Project (1953), the Fort Henry Apron Studies (1960), and Moore and Masch (1962).

2.5.3 Review

This survey has shown that the erodibility of cohesive soils depends upon a complex interrelation among their physico-chemical properties which, it seems, cannot be consistently represented by only one or a few of these properties. Evidence from the literature, however, shows that, in a given soil, the ultimate effect of these physicochemical properties is to influence shear strength. Previous and recent studies of erosion clearly support the importance of shear strength.

Shear strength is therefore used in this study as the main indicator of the erodibility of channel banks. Although the effects of root growth and rooting density are known to influence aggregate stability and shear strength respectively, their influence has not been tested in known previous studies of erosion. In this study therefore, the influence of roots on shear strength is also investigated.

2.6 The Effect of Vegetation on Scour

In the previous sections, the discussion on channel bank erosion by flowing water has emphasised the importance of the properties of the bank material exclusive of vegetal effects. In this section, the discussion is concerned with the effects of the vegetation in channels on the flow characteristics which cause scouring.

In vegetated channels the most important hydraulic characteristic of the vegetation is the resistance it offers to the flowing water. The immersed foliage roughness elements retard and dissipate flow velocity or stress and this may promote sufficient attenuation of flow to prevent scour. However, the hydraulic resistance of vegetated open channels is still only imperfectly understood (Bache and MacAskill, 1981; Webber, 1971). A commonly used means of estimating hydraulic resistance in vegetated channels employs Manning's equation:

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad (2.3)$$

Where:
- V = The mean velocity (m/s)
- R = The hydraulic radius, defined as the cross-sectional area divided by the wetted perimeter
- S = The sine of the channel bed slope
- n = The Manning roughness coefficient or retardance.

The first systematic investigation of hydraulic resistance in vegetated channels employing Manning's equation was begun by the U.S. Soil Conservation Service in 1936 at the Spartanburg Soil Conservation Laboratory. The findings have been reported by Cooke and Campbell (1939), Palmer (1945), Ree (1949), Ree and Palmer (1949), and in the U.S.D.A. Handbook of Channel Design for Soil and Water Conservation (1954).

The results of these studies show that the hydraulic retardance of a vegetation varies very widely because it depends on depth of flow. During flows of very small depth, the initial vegetal resistance is relatively high. As flow depth increases in the low flow range, in which the vegetation is erect and not submerged, flow retardance values, n, increase gradually to a maximum value. This increase in n with depth of flow is due to the greater bulk of vegetation encountered as flow depth increases in the channel. As flow is further increased, a depth is reached when vegetation bending and submergence starts. With continued increases in depth of flow, n starts to decrease rapidly. When the vegetation is submerged and flattened, n tends to become more or less constant with further increases in flow depth. The studies also show that n varies with the shape and bedslope of the channel, and the type of vegetation, and that for a given vegetation, the hydraulic resistance depends on the condition of growth. These findings show that the estimation of scour resistance in vegetated channels using this velocity approach is not entirely satisfactory because variations in n seem to depend on too many variables.

However, the variation of Manning's n with the product of mean velocity (V) and the hydraulic radius (R) was investigated for different grass vegetation conditions (Ree and Palmer, 1949). According to Kouwen and Li (1980), no theoretical justification is given for this approach. Palmer (1945), however, observed that the hydraulic behaviour of a vegetation is determined by the bending moment exerted by the flowing water. He therefore argued that "with this moment [being] a function of depth and velocity it is reasonable to use their product as an indication of probable hydraulic behaviour as expressed in the retardance coefficient n." In these experiments, each grass condition was investigated in channels with different geometries. The results of the n-VR plots produced a trend showing that Manning's n decreases as VR increases. More important was the finding that this relationship was unique for each vegetation type regardless of the channel geometry. It was further found that vegetation of similar characteristics would have similar n-VR curves. It was noted however that "Beyond VR values of 3 and 3.5 for short and long Bermuda grass, respectively, the retardance coefficient ceases to be associated with VR (Ree, 1949). Ree (1958) later confirmed the n-VR relationship for row crops in diversion terraces.

The finding that the hydraulic resistance, n, can be predicted for a given vegetation condition by the product VR led to a classification of vegetation on the basis of n-VR curves. Five such classes of vegetal retardance were identified and given letter designations ranging from A (very high retardance) to E (very low retardance). The physical characteristics of the vegetation in each of the classes are given in terms of 'length of vegetation' and 'stand'; the latter is described in qualitative terms such as 'good' or 'fair'. To estimate the hydraulic resistance, n, for any vegetation, one compares the physical characteristics of one's vegetation with those of the given classification and selects its retardance class. The prepared n-VR curve for that retardance class will then provide the desired estimate. A diagram has been prepared for each class which provides a direct solution of Manning's equation. These computations and curves have since been presented in Chow (1959), Palmer (1945), Ree and Palmer (1949), and by the U.S.D.A. Soil Conservation Service (1954) as a part of the permissible velocity design procedure. Since their presentation the n-VR approach has provided channel designers with a useful tool which, according to Temple (1982), appears to account correctly for the dominant characteristics of flow over submerged grass. Temple (1982) has however observed that the treatment of Manning's n as a unique function of the VR product for any given grass lining represents a simplification of the complex interaction of the flow with the vegetal elements.

Many investigators have since questioned the n-VR method and have put forward various analytical flow resistance models for vegetated channels, based on studies with artificial vegetal elements (Kao and Barfield, 1978; Kouwen and Li, 1980; Kouwen et al, 1981; Kouwen and Unny, 1973; Petryk and Bosmajian, 1975; Thompson and Roberson, 1976). Kouwen and Li (1980) refer to Eastgate's (1966) results which show that, for a particular grass, the plotted points of n-VR do not always fall along a single line. These experiments were conducted in flumes lined with Australian grasses and tested at slopes smaller than those used in the n-VR experiments. They also present plots of n Vs VR for artificial plastic roughness elements which they interpreted as showing that the n-VR approach is deficient when conditions other than those specifically tested are used. Kouwen et al (1981) would rather the n-VR method be dropped in favour of a numerical method which they put forward; but at the same time, they state in their conclusion that "... the correlation of Manning's n with the product of mean flow velocity and hydraulic radius is valid for most conditions encountered in practice." One would have thought therefore, that they would have suggested that their method be used for those slope and flow conditions for which they say the n-VR approach is deficient. However, it can be argued that there is no common ground for comparing results from experiments using simulated vegetation in flumes with those from actual vegetation tested in channels although this would not apply to observations based on Eastgate's (1966) results.

The analytic approaches have undoubtedly increased understanding of flow in vegetated channels but they have resulted in flow resistance models in terms of parameters that are not easily measurable in the field. For instance, Kouwen and Unny (1973) found that Manning's n is a function of a relative roughness expression defined as the deflected roughness height divided by the flow depth. They however accept that the deflected roughness height is difficult to determine in vegetated channels because it depends on the stiffness of the vegetation which can only be known by comparing the bending characteristics of the vegetation to the known bending characteristic of an artificial element. Kouwen and Li (1980) confirm the importance of the stiffness parameter by showing that very stiff vegetal elements can have the same effect on n as very dense vegetation. Thus, vegetation with low stiffness and high density can have the same n value as vegetation with high stiffness and low density.

Temple (1980, 1982) discussed some of the deficiencies of the n-VR method and proposed (1980) the use of the tractive force approach (Section 2.3.2) but modified so that the hydraulic resistance in vegetated channels is partitioned into the resistance associated with grain, form and vegetal roughness. The form roughness would not be considered important for channels without marked changes in boundary configuration. Similar partitioning of flow resistance has been done by Fenzl and Davis (1964), Petryk and Basmajian (1975) and Thompson and Roberson (1976). This approach is based on the assumption that the concept of frictional linearity (Einstein and Banks, 1950) may be applicable in vegetated channels. The salient feature of this concept is that a linear relationship can exist between total resistance to flow and the resistances contributed by two or more roughness elements of dissimilar resistance characteristics. In a vegetated channel, since the two main roughness components are the vegetation and the soil, the assumption is that, in the broader sense of the concept, the total resistance to flow (n) is a function of these two components, so that the relationship: $n = n_s + n_v$ holds

where: n_s = the resistance due to the soil

n_v = the resistance due to the vegetation.

This line of reasoning led Temple (1980) to develop the following tractive force equation to estimate what he called the effective shear stress at the soil-water interface.

$$TF_e = WDS \quad (1.0 - C_F) \left({}^{n_s}/_{n} \right)^2 \tag{2.4}$$

Where: TF_e = The effective shear stress at the soil-water interface

W = The unit weight of water

D = The flow depth

S = The slope of the channel

C_F = An empirical parameter or vegetal cover factor describing the potential of the vegetal cover to dissipate turbulent eddies before they impact the soil boundary

n_s = Manning's resistance coefficient associated with the soil only

n = Manning's resistance coefficient for the channel

The main advantage of this approach over the currently used permissible velocity approach is that it is related only to the properties of the soil boundary whereas the permissible velocity is necessarily related to the soil properties, the vegetation characteristics and channel geometry. Temple (1980) however points out that the classification of the vegetation parameters used in developing his equation may not be analytically complete even though the conceptual framework of the approach may be sound. Gregory and McCarty (1986) agree that the approach is conceptually sound but point out possible weaknesses associated with the empirical vegetal cover factor, C_F. Particularly, they observe that because no procedure is given to determine the cover factor, it would seem that this parameter is an empirical coefficient that must be experimentally determined for each type of vegetation. Since in this study the flow retardance of all the vegetation density samples will be determined, the use of the cover factor will not be necessary. Consequently, equation (2.4) will be modified accordingly and used in this study to estimate the effect of root-permeated soil surfaces on scour.

2.7 Slump Erosion

Slumping, the commonest form of mass erosion from slopes, is a gravity-controlled mass movement. It has been described by Varnes (1958) as a slide phenomenon in which there is a downward and outward movement of slope forming materials along internal and circular slip surfaces. The moving mass, which can be made up of one or a few units, is usually not greatly deformed.

2.7.1 Slump Stability Factors

The factors that influence the stability of earth slopes against mass movements in general, have been grouped into those that contribute to high shear stress and those that contribute to low shear strength (Varnes, 1958). Sharpe (1938) has summarised these factors into passive and active categories. The approach adopted here is to discuss, in an interrelated way, the factors that increase shear stress and decrease shear strength (disturbing forces), and those that increase shear strength (resisting forces). This is because in slope stability study, it is the balance between these forces that determines the stability of the slope. The factors that influence the stability of channel banks in a material of given strength include the interactions among the following: bank geometry, flow, surcharge and vegetation.

2.7.2 Bank Geometry

The main aspects of geometey that influence stability are slope angle (B) and bank height (H). All other factors being equal, steep slopes and/or deep banks are more unstable than gentle and/or shallow ones. This is because it is the increase in the magnitude of the downslope component of gravity acting on the slope material that causes its movement. The downslope component of gravity acting on material on a given slope is simply related to the product of the weight of the material (W) and the sine of the angle of inclination (sine B). As the slope gets steeper, sine B increases, causing the downslope component of gravity to increase and stability to decrease. Similarly, as the bank gets deeper, W increases, thereby increasing the gravity force leading to instability.

In the equilibrium method of Total Stress analysis of simple homogeneous cohesive banks, the factor of safety against sliding with respect to shear strength is directly related to the product of a dimensionless stability number (N) and cohesion (C), and inversely related to the product of the bulk unit weight of the material (BD) and the slope height (H) (Janbu, 1954; Terzaghi and Peck, 1967). For stability to increase, the product (NC) should increase whilst the product (BD.H) should decrease. However, the dimensionless stability number depends mainly on the slope angle; as this angle increases, as in the steepening of banks, the value of the stability number decreases and hence stability decreases. Also, as the height of the bank increases, as in the deepening of banks, the product (BD.H) increases and hence stability decreases. Thus in channel banks, the slope angle and the bank height are the main geometric factors that influence stability. They can probably become critical factors during periods of heavy precipitation, when matric potentials can rise to zero. Under such conditions, the bulk unit weight increases to a maximum and cohesion can be reduced to a minimum. This can result in widespread instabilities of banks, as observed by Little et al (1982).

2.7.3 Flow

The main flow factor that influences channel bank stability is tractive stress. Additionally, flows affect bank stability through wetting. The magnitude of these effects depends upon flow discharge as it affects flow depth and the bank surface area that is wetted. Flows attack the lower banks more frequently than the upper banks; in addition, at bank full discharge, the lower banks may experience higher boundary tractive stresses than the upper banks. This is because tractive stress is a function of flow depth (Chow, 1959). The net effect of these events is to cause scouring of the bed and undercutting of the lower banks, thereby destabilising the upper banks which subsequently slump into the channel after the peak flow has passed (Gupta and Fox, 1974; Hooke, 1979). These processes become even more efficient in causing slumps when high flows of long duration or high frequency act upon banks that have been thoroughly wetted by precipitation or previous flows (Little et al, 1982; Wolman, 1959), and/or preconditioned by the effects of freezing temperatures (Lawler, 1986). These are probably the reasons why Knighton (1973) found that winter storms, which were individually of lower magnitude than the summer flows, were more effective in eroding banks. Also, in addition to the thorough wetting in winter, shear stresses for a given flow depth may be higher during winter, due to the higher viscosity of the flowing water; hence, lower shear stresses are required for eroding the already weakened bank material. From this discussion, it seems that the degree of bank material preconditioning should always be considered in relating bank material stability to discharge characteristics.

2.7.4 Soil Moisture Surcharge

The influence of soil moisture surcharge on slope stability has already been touched on as it affects the efficiency with which tractive shear stresses cause bank slumping. Increasing surcharge, due to the weight of precipitation water and rises in ground water, influences slope stability mainly through overloading, inducing high positive pore water pressures and lubricating shear planes within the bank material. Overloading of slopes increases the bulk unit weight of the slope material; positive pore water pressures decrease the cohesion between soil particles whilst the lubrication of shear planes decreases interparticle friction (Gray and Leiser, 1982). The net effect of surcharge, therefore, is to decrease the shear strength of the slope material and thus make it more susceptible to slumping.

2.7.5 Vegetation

The possible ways in which vegetation may influence slope stability are; root reinforcement of soil and root wedging, soil moisture modification, buttressing and arching, surcharge from the weight of trees and wind throwing in trees.

i. Root reinforcement and Wedging: The most important way in which vegetation is known to stabilise soil is by root reinforcement. An increased understanding of this role has come about as a result of field and laboratory studies of fibre- and root-permeated soils by Endo and Tsuruta (1968), Kassiff and Kopelovitz (1968), Waldron (1977) and Wu et al (1979). Kassiff and Kopelovitz (1968) used plastic fibres embedded in compacted soils and found that for specific soil conditions, cohesion was increased by the fibres whilst the angle of internal friction did not alter considerably. They also found that an increase in the density of the fibres in the soil considerably increased the cohesion of the soils tested. Endo and Tsuruta (1968) sheared root-permeated soils in the field and found that young European alder trees (Alnus glutinosa) greatly increased shear strength by mainly increasing the cohesion of the soil pedestals sheared. Waldron (1977) has also measured the soil reinforcing effects of three plant species in the laboratory and found that at 30 cm depth, the roots of all three plants (alfalfa, barley and yellow pine) substantially increased the shear strength of the soils but by different amounts. He found that alfalfa roots provided the highest reinforcement by increasing shearing resistance relative to root-free soils by as much as 290%. It is not however clear from his work whether this superiority of alfalfa over the other plants was due to differences in rooting density because no such data were presented. From his stability analysis based on the data, he concluded "...that roots can increase the factor of safety of a given circular surface by reinforcing those parts of it within the root-zone and thereby increase stability of deeper soil masses." Wu et al (1979) also used laboratory data to determine the effect of roots on shear strength and slope stability and found that"...shear strength contributed by tree roots is important to the stability of the steeper slopes."

Wu et al (1979) have presented a theoretical root-reinforcement model for predicting the contribution of tree roots to soil shear strength. Similar models have been put forward, apparently independently, by Waldron (1977) and Gray and Leiser (1982). The assumptions on which the model is based are critically discussed by Greenway (1987). According to this root-reinforcement model, when soil is sheared, a tensile force develops in the roots which can be resolved into a tangential component which directly resists shear and a normal component which increases the confining stress on the shear plane. The tangential stress component at the soil-root interface is assumed to have a maximum value at incipient failure or slippage (Gray and Leiser, 1982). In other words the model assumes that at failure the tensile strength of the roots in the soil is fully mobilised so that the roots break in tension rather than pull out. The model also assumes that the soil friction angle (ϕ) is not affected by the reinforcing effect of the roots and consequently, that the mobilised tensile strength of the roots is approximately equal to cohesion. It is not known, however, whether this assumption has been experimentally verified either for tree roots or grass roots. It is mainly based on the fact that linear reinforcements in soils have been shown mainly to increase cohesion (Bache and MacAskill, 1984; Gray and Leiser, 1982;

Waldron, 1977; Wu et al, 1979). But it is debateable whether the effects of live roots can be said to be the same as the effects of inanimate objects in soils. Nevertheless, according to the model, the mobilisation of tensile resistance in roots therefore translates into a shear strength (cohesion) increase in the soil as represented by the equation - for roots all of one diameter:

$$Cr - 1.15\ tr \tag{2.5}$$

Where:

Cr = Roots contribution to shear strength

tr = The average tensile strength of all the roots per unit area of soil, and is determined from:

$$tr = T_R(A_R/A) \tag{2.6}$$

Where:

T_R = The average tensile strength of the roots.

A_R/A = The root area ratio, defined as the cross-sectional area of all the roots in the soil (A_R) divided by the cross-sectional area occupied by the roots (A).

When there is a distribution of root-sizes in the soil, then the variation of tensile strength in the different root size classes has to be accounted for. In this case, tr is determined by a summation of Equation 2.6 over all root sizes and their respective tensile strengths. In stability analysis, the total shear strength of the soil-root system (Sr) is found by adding the predicted increase in shear strength due to roots to the cohesion term in the Coulomb Equation to give:

$$Sr = (Cs + Cr) + \sigma \tan \phi \tag{2.7}$$

Where Cs is the cohesion of the root-free soil.

Waldron and Dakessian (1981) have extended the root-reinforcement model to accommodate a range of root diameters and also to account for the possibility that roots loaded in tension, when the soil around them is sheared, may not only stretch or break, but may also slip through the soil. Increases in shear resistance which the model predicted from the tensile strength properties of barley and yellow pine roots were compared with the measured shear resistance difference between saturated root-free and root-permeated clay loam soils. From the comparisons, it was found that " ...root tensile failure did not occur during shear of [the] saturated clay loam permeated by pine and barley roots." It was therefore concluded that "Root slippage rather than breakage must be the most common condition limiting reinforcement or strengthening of saturated fine-textured soil by roots." Another finding which is particularly important to this study is that at small shear displacements, choices of the magnitude of the root-soil bond, an unmeasured model parameter that is assumed constant, led to an underestimation of root reinforcement values as compared to measured values. This finding was believed to be partly due to the fact that the assumption that the strength of the soil-root bond at failure is constant is not correct and partly due to the fact that other rooting effects apart from tensile strength "...may have structurally altered the soil in the root-zone producing some indirect root effect on soil strength" which the model could not fully account for. This clearly indicates a need for a better understanding of the effects of roots not only on the mechanical properties of soils but also on the physical and probably chemical properties of the soil that could affect shear strength. For instance other rooting effects that could significantly increase the magnitude of the soil-root bond include adhesion and improvements in aggregate, and hence, structural stability (Reid and Goss, 1980, 1981). These root strengthening effects may be of different kinds and magnitudes in different soils, and for the same soil the effects may also be moisture dependent.

Other investigators have recognised this strengthening role of vegetation roots without quantifying its effect. Chorley (1959) listed the "amount of vegetative binding" as one of the factors affecting soil shearing resistance. Dickinson and Scott (1979) found that "when land adjacent to the bank is well protected by crop cover...., even highly erodible soil remains relatively stable."

For some investigations, the root effect did not help in data collection. Flaxman (1963) observed that"... the number of sites was partly limited by the necessity of finding locations relatively free of vegetation." In selecting sites for bank erosion measurements, Hooke (1979) found that "...the vegetated sections remained completely stable and are much less suitable for measurements by pins."

In addition to these, there is a growing pool of strong indirect evidence in support of root contribution to slope stability against mass movements. This evidence comes from studies on the effect of vegetation removal on slope stability by Brown and Sheu (1975), Burroughs and Thomas (1977), Gray (1970, 1974), O'Loughlin (1974) and Wu et al (1979). Their findings are all similar. They note a significant increase in the frequency of mass movement after vegetation removal and attribute this to the destruction of the interconnected root mass in the slope by the gradual root decay. This reinforces the view that tree root strength tends to reduce the incidence of landsliding more than the other effects of trees tend to increase it. Hence trees growing on hillslopes inhibit slides in their vicinity.

However it is known that vegetation roots may also destabilise soil through root wedging. This refers to a process whereby roots tend to loosen the soil by growing in cracks and fissures. The effect of this process on slope stability is presently not well understood (Gray, 1970). The preponderance of evidence from published studies, however, seems to show that the beneficial effects of roots far outweigh any possible adverse effects.

ii. Modification of Soil Moisture: Vegetation modifies soil moisture by limiting the build up of soil moisture stress. Trees deplete soil moisture to considerable depths and so develope large moisture deficits thereby increasing shear strength (Gray and Leiser, 1982). These positive aspects of soil moisture modification occur mainly through transpiration. It is therefore concluded that, all other things being equal, a forested slope might not reach critical saturation, nor exhibit such high positive pore water pressures after storms as quickly as a denuded slope (Gray, 1970).

Evidence in support of this comes from observations that soil on cut-over slopes often possesses a higher moisture content that on forested slopes due mainly to their relative transpiration rates (Bache and MacAskill, 1984; De Ploey, 1981b, Gray and Leiser, 1982). Other evidence is that during heavy rains mass movements are much more frequent on cultivated or cutover slopes than on forested slopes (DePloey, 1981b; Gray, 1970; Wu et al, 1979).

However, the importance of this role of moisture depletion by vegetation with respect to slope stability, especially during storms, has been a subject of differing opinions. DePloey (1981b) has presented a view that the total effect of evapotranspiration during a limited time-span of several rainy days is negligible. This, he explains, is because interception and the attendant vaporisation cause a compensating reduction in transpiration so that there will be no net evapotranspiration losses. In addition, he has indicated that vegetation inhibits overland flow and that since roots facilitate the infiltration of water, the moisture content of the soil will be increased, thus lowering the shear strength of the soil. Waldron (1977) believes that during periods of heavy precipitation this effect may be offset by stabilisation of the soil through root reinforcement even though, during such periods, matric potentials can rise to zero irrespective of vegetation. Further support for this view has come from Bache and MacAskill (1984) and from Gray (1977) and Rice and Krammes (1970) as reported by Gray and Leiser (1982). Rice and Krammes (1970) consider the effect of soil moisture depletion by evapotranspiration to be negligible in climates where precipitation greatly exceeds potential evapotranspiration. The study by Gray (1977) indicates ".. that the forest cover has little effect on the soil moisture regime once precipitation of sufficient duration and intensity falls on the slope. Tree cover at the site at least does not appear to have much influence on the probability of catastrophic landsliding during these storms."

From the foregoing discussion, two things emerge. Firstly, vegetation plays an ambivalent role in modifying soil moisture surcharge in slopes and secondly, the net effect of these contrasting roles on slope stability is uncertain. There is thus a need to quantify more precisely the role of soil moisture modification by vegetation for a better understanding of the net effect on slope stability.

iii. Weight of Vegetation: The effect of surcharge due to the weight of trees on slope stability is another controversial subject. DePloey (1981b) says that the weight of trees can have a destabilising effect on slopes. He argues that very tall and large trees can exert an appreciable supplementary load, several Kg/cm^2, on a limited portion of the soil directly beneath a tree and that this increases the probability of slope failures. Another view is that surcharge due to the weight of trees "...would appear to increase shear stress but this is largely negated by a concomitant increase in shear strength due to the confining effect of surcharge..." (Gray, 1970). Bache and MacAskill (1984) also hold this view. In addition, Gray and Leiser (1982) and Wu et al (1979) believe that the effect of surcharge due to the weight of trees will in any case have little or no effect on calculated factors of safety.

Gray and Leiser (1982) accept that surcharge as high as 200 psf (0.1 Kg/cm^2) can be expected locally beneath a tree. In one case study they calculate a surface loading stress under a tree to be 1400 psf (0.7 Kg/cm^2). When this value was distributed over an area of about 7 sq.m with a tree spacing of 9m, they calculated that surface loading would produce stress increases of 0.01 Kg/cm^2 at 1.5m depth and 0.037 Kg/cm^3 at 6m depth. From these values they concluded that "...the influence of surcharge from the weight of trees on either creep rates or safety factors in long slopes is not likely to be very significant one way or another."

Wu et al (1979) used a value of 77 psf (0.038 Kg/cm^2), an average calculated from Bishop and Steven's (1964) value of 50 psf (0.025 Kg/cm^2) and his own value of 105 psf (0.05 Kg/cm^2) by dividing the weight of the trees by the area of the root mat.

From this discussion it is evident that none of the surcharge values used are based on stress directly beneath trees. Judging from the varying magnitudes of the values expected to occur under trees, De Ploey's (1981b) suggestion of several Kg/cm^2 for apparently much larger trees, may not seem unreasonable. Nevertheless, these surcharge values due to the weight of trees need to be derived for various average tree sizes under different slope angles in order to determine the circumstances under which trees may or may not destabilise soil material through their weight.

iv. <u>Buttressing and Arching</u>: Vegetation also influences slope stability through buttressing and soil arching by the trunks of trees growing in slopes. Arching occurs when soil attempts to move through and around a row of trees firmly embedded in an unyielding soil layer (Bache and MacAskill, 1984; Gray and Leiser, 1982). The embedded stems also act as buttress piles or abutments, restraining soil movement from trunks, thereby counteracting the downslope shear stress (Gray and Leiser, 1982). However the significance of these processes in slope stability is not fully understood.

v. <u>Windthrowing:</u> Windthrowing is believed to have an adverse effect on slope stability (Bache and MacAskill, 1984; Gray and Leiser, 1982; Murgatroyd and Ternan, 1983). Strong winds blowing downslope through trees can exert an overturning moment on the trees which creates localised disturbances in the slope material. Bache and MacAskill (1984) acknowledge that wind throwing can be a serious problem in slope stability. Gray and Leiser (1982) accept that it is a fairly common occurrence in some forests but observe that it affects mainly aged or diseased trees.

Wu et al (1979) reported the work by Hsi and Nath (1970) in which they measured the drag force of wind on trees in experiments with model forests in a wind tunnel. This work led to a relationship for calculating wind stress on trees. Wu et al (1979) used this relationship to calculate the stress for a wind velocity of 90 Km/hr and found that, "The amount is rather small and not likely to exert a strong influence on stability." Brown and Sheu (1975) have also outlined a theoretical framework for analysing wind forces in trees. Nevertheless, according to Gray and Leiser (1982), "The total downslope force created by a wind blowing through a stand of trees, and hence its overall effect on slope stability, has never been evaluated." Research is therefore needed to determine the overall effect of windstress on forests and hence on slope stability.

2.7.6 Synthesis

This review of the effects of vegetation on the stability of slope material has brought out two main points. Firstly, many effects of vegetation, especially tree vegetation, are not yet well understood. Secondly, and pertinent to this study, soil reinforcement by the roots of trees and shrubs is undeniably important in increasing the stability of slopes generally. However, this study is about the effects of grass vegetation on channel bank stability. Clearly, grasses do not have most of the destabilising influences on slopes discussed for trees and, grasses establish on slopes quicker than trees; this makes grasses preferable to trees for stabilising banks. Little previous work has been concerned with the effects of grass roots on channel bank slopes. Since grasses are commonly employed in channel bank stabilisation projects, this study will attempt to evaluate the effect of grass roots on the stability of channel banks.

But in this study, the root density rather than the tensile strength approach will be used in assessing grass root contribution to soil shear strength. This is partly because of the present uncertainties on whether the assumption that the tensile strength effect of the roots is fully mobilised in failure is valid, as discussed in Section 2.7.5.(i), and partly because of the measurement problems that would be involved in the determination of root diameters and tensile strengths of the very large number of fibrous roots that will have to be counted. Greenway (1987) has discussed some of these problems even with tree roots which have the advantage of being larger and also fewer per unit volume of soil than fibrous roots. Because of these considerations, the procedure adopted in this study is simply to measure directly, in situ, the shear strength of the root-free soils and subtract it from the measured shear strengths of soils permeated with different densities of live roots to get the root density contribution to soil shear strength.

CHAPTER THREE

EXPERIMENTAL DESIGN AND METHODOLOGY

3.1 Introduction

A laboratory approach to this study of vegetation effects on bank stability is preferred over field investigations because of the need, when working on problems about which little is known, to control the factors influencing the processes involved. In this study, it is necessary to control structural variations in the soil so that their effect on shear strength and on flow can be regarded as uniform for all samples; it is also necessary to control moisture content and variations in rooting density so as to evaluate their effect on shear strength changes more accurately. Root and vegetation density variations need controlling in order to determine their effects on controlled flows. In field studies, these experimental variables cannot be easily controlled. In addition, there can be other effects and factors in the field which may not be readily apparent or which may be difficult to evaluate. The laboratory approach is also used so that the interactions among the experimental variables can be better evaluated under simplified or simulated conditions.

This study is divided into three separate but related single factor experiments based on the shear vane, the torsional shearbox and the flume. The vane experiments are designed to determine the nature of the shear strength - moisture content relationships for soils containing different densities of live grass roots. The torsional shearbox experiments are designed to determine the magnitude of the contributions which varying rooting densities make to the cohesional and frictional strengths of soil at zero matric potential - the moisture potential at or beyond which bank materials are most vulnerable to scour or slumping. The flume experiments are designed to determine the critical tractive forces at which samples containing differing vegetation and rooting densities remain stable and to evaluate the relative contributions which the root and shoot systems make to the total tractive resistance of vegetated channels to flowing water.

3.2 Experimental Design

For all the experiments, wooden boxes, 1m long x 30 cm wide x 15 cm deep, were used to hold soil samples. These dimensions were dictated by the internal dimensions of the flume in which the flow experiments were conducted. The wooden boxes were filled with air dry soils which were ground to pass through a 2-mm sieve; this was done to minimise soil structural variability which could significantly influence variations in either shear strength, tractive force or flow retardance within and between sample treatments. The soil was levelled off but not compacted except for settlement under its own weight. From experience gained in a pilot study, it was found necessary to fill the boxes to 2 - 4 cm below the brim so that the samples could be ponded for either saturation or zero matric potential to be reached.

The soil samples were then sown with Lolium perenne (Loretta) grass seeds in a staggered pattern (Figure 3.1) for maximum flow retardance (Hartley, 1980; Li and Shen, 1973); the control boxes were not seeded (Plate 3.1). Thus, vegetated and bare channel bank conditions were simulated. Loretta is a perennial amenity grass. It is used in this study mainly because it is known to establish quickly and to form a strong root mat (Dr. R.M. Morris, Open University; British Seed Houses Ltd; Personal communications). This latter property was particularly useful in providing the kind of increases in root density that are likely to produce significant effects on soil shear strength. In addition, this grass has been successfully used in experiments by Reid and Goss (1980, 1981) on the influence of roots on soil aggregate stability.

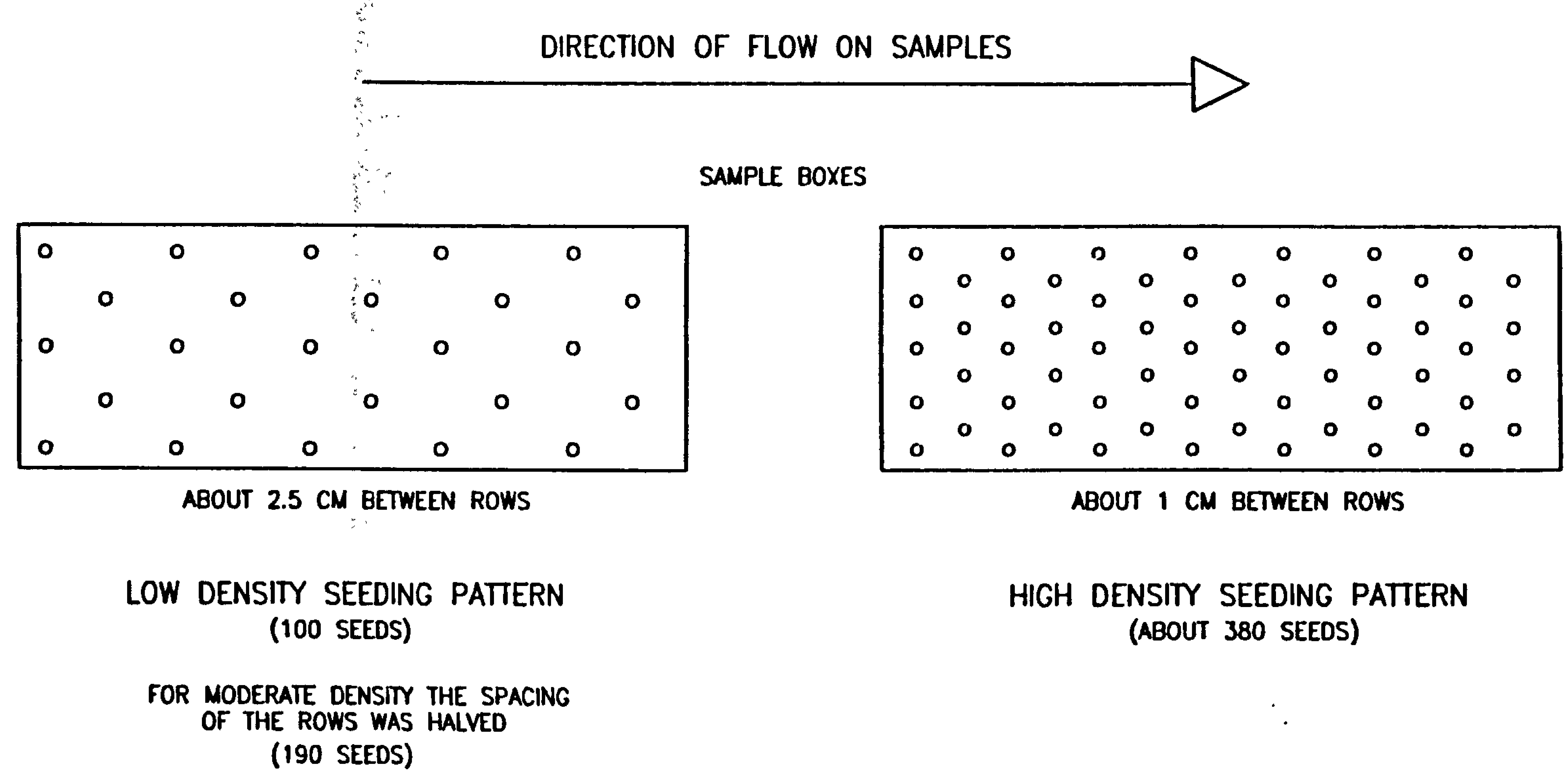


FIGURE 3.1 SKETCH OF STAGGERED VEGETATION SEEDING PATTERNS USED IN THE STUDY

PLATE 3.1 <u>SAMPLE BOXES AND MERCURY TENSIOMETER</u>

(Note Tensiometer in Central Box which contains soil cleared of vegetation)

In order to produce conditions with a wide range of root densities at any one time, the samples were seeded at different densities of 100, 190 and 380 seeds per sq.m. and left to grow in a greenhouse for periods of 4, 8, 12, 16 and 20 weeks for the sandy clay loam soil, and for 4, 6, 8, 10, 12, 14 and 16 weeks for the clay soil, before tests were performed on them. For the sandy clay loam soil, there were 17 samples for each experiment (Total - 51 samples) whilst for the clay there were 10 samples for the vane, and 12 samples for each of the tortional shear and flume experiments (Total - 34 samples).

For the flume experiments, an existing 6 m long x 31 cm wide x 31 cm deep indoor Armfield circulating flume was used. The flume has a rigid bottom and transparent sides through which observations of the sample surfaces can be made during tests. At the upper end of the flume is a stilling basin which is separated from the flume section by a honeycombed baffle to dissipate the turbulence of the incoming flow. The flow through the flume is regulated by means of a wheel located underneath; this makes it possible to subject different samples to approximately the same flows. The flume also has another wheel which regulates the bed slope from level to a maximum inclination of about 2^o. This maximum slope was used for all the experiments.

Since the flume has a rigid rather than a false bottom, the sample boxes could not be placed directly in the flume for the experiments. Therefore a 4 m long and 18 cm high test section was constructed in the upstream end of the flume. The section consisted of a 2.5 m long approach box covered with perspex to ensure a more uniform approach flow, then a metre long section for placing the sample box and a 0.5 m section for a downflow box to avoid a rapid drop of flow at the downstream end of the sample. All boxes were the same height as the sample boxes. Thus, water flowing directly over the approach box would flow over the sample and the downflow boxes without significant changes in flow pattern. Uniform flow existed for all the flows and was verified by determining that for a given discharge the average on-coming flow velocities and depths were relatively constant throughout the flow section (See Section 3.5). Plate 3.2 shows the flume section and related measurement apparatus.

3.3 Methodology

It was desired to conduct this study with reference to two cohesive soils which are different in terms of their cohesiveness and the ease with which the aggregates dispersed in water - properties which are known to significantly influence erodibility (Grissinger, 1966; Smerdon and Beasley, 1959). Soils were collected from the top 20 cm of the surface from two different soil series on farms near the Silsoe College campus. The clay belongs to the Wicken Association and Soil series; it is calcareous and drains poorly, having been derived from a chalk marl parent material (King, 1969). It was used mainly because it formed the banks of a small channel, the geometric properties of which are used in the bank stability analysis. The sandy clay loam belongs to the Brown earth Series of the Flitwick Association; it is freely drained and is derived from the Lower Greensand parent material (King, 1969). These soils are not dissimilar from the range of materials that are known to compose channel banks (Siebert, 1968).

The soils were air dried and the following physical characteristics determined in the laboratory: Particle size analysis by the pipette method, Atterberg Limits by the Casagrande and cone methods, Dispersion ratio (ADAS, 1982) and Aggregate stability by the wet sieving method (ADAS, 1982; Kemper, 1965). These results are presented in Table 3.1.

3.4 The Vane and Torsional Shear Box Experiments

As seen in Chapter 2, recent interest has been shown in expressing the erodibility of soils in terms of their inherent shear strength characteristics. According to Coulomb's theory of failure,

(A) Incoming Flow Section (Red); Sample Box (dark); Down flow Box (light). Photo was taken during a flow experiment (Flow towards viewer)

(B) Depth probe (nearer viewer) and flow meter on box.

PLATE 3.2:

FLUME SECTION SHOWING VELOCITY METER AND DEPTH PROBE

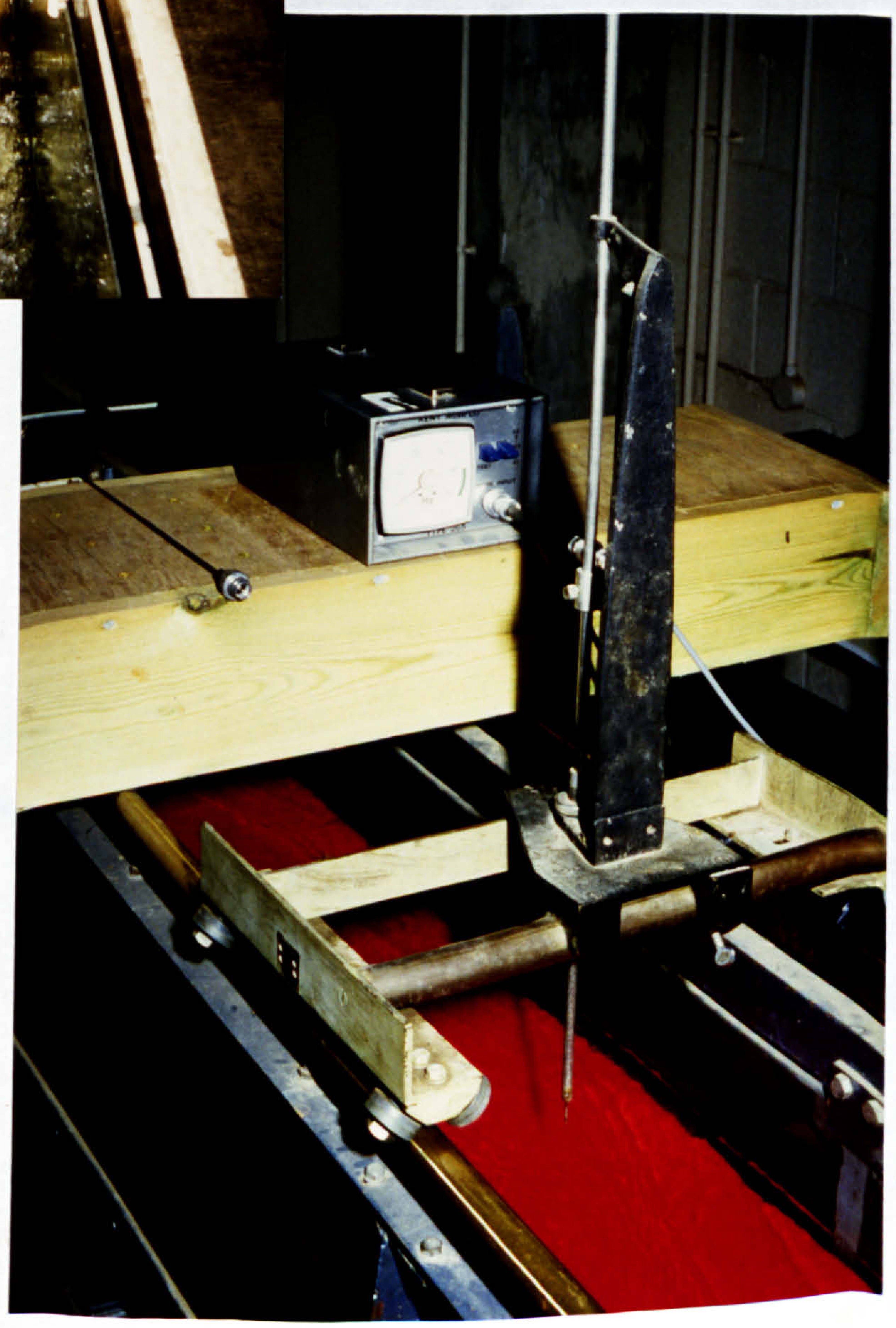


TABLE 3.1:

PHYSICAL CHARACTERISTICS OF FIELD SOILS

SOIL CHARACTERISTICS	SANDY CLAY LOAM	CLAY
% Coarse Sand > 600 microns	7.85	3.92
% Sand 600 - 212 microns	40.45 -77.44	8.44 -19.11
% Fine Sand 212 - 63 microns	23.14	6.75
% Silt < 63 microns	15.84	26.97
% Clay < 2 microns	12.72	53.92
% Organic Matter	3.73	4.33
Plastic Limit	10.00%	30.00%
Liquid Limit	30.00%	70.00%
Plasticity index	20	40
Dispersion ratio (%)	14	9.0
Water stable aggregates % > 0.5mm	10	35

shear strength can be expressed as:

$$S = C + \sigma \tan \phi \qquad (3.1)$$

Where: S = The shear strength
C = The cohesion
σ = The normal stress on the plane of failure
ϕ = The angle of soil friction.

These experiments are therefore concerned with the measurement of the shear strength of root-free and root-permeated soils at zero matric potential and at lower moisture contents as the soils dry out. In addition, it is required to determine the magnitude of the cohesion contributed by differing rooting densities at zero matric potential only. It is also desired that the measured strength parameters be as representative as possible of those existing in the conditions simulated by the vane, torsional shear box and flume experiments because only then can the shear strength values be of any real interpretational value (Grissinger et al, 1981; Payne and Fountaine, 1952; Skempton and Bishop, 1950). This, therefore, means choosing a shear strength measuring method that can be used in situ and that can give not only total shear strength, but also its cohesional and friction components.

Under these conditions, the National Institute of Agricultural Engineering (NIAE) pattern torsional shear box, which was developed to give in situ shear strength at various normal stresses (Payne and Fountaine, 1952), seems the most suitable (Fountaine and Brown, 1959; O'Callaghan et al, 1965; O'Sullivan and Ball, 1982; Schafer et al, 1963). All other frequently used methods of determining shear strength such as the triaxial and translational box (Skempton and Bishop, 1950; Smith, 1981) require the use of disturbed samples, the strengths of which may not reflect the true in situ strengths of the soil being tested. A pilot study, however, showed that the torsional shear box was unsuitable for determining shear strength of the soils in the sample boxes with low or very low moisture contents because a very wide area of the soil around the torsional box is disturbed when taking measurements. It was therefore decided to use the torsional shear box to measure shear strength at zero matric potential only, and to use the shear vane for determining shear strength variations with moisture content.

The shear vane is known to measure cohesion in frictionless soils (Hansen, 1950; Payne and Fountaine, 1952; Skempton and Bishop, 1950) and to give more consistent results than triaxial tests in these soils (Serota and Jangle, 1972). The shear vane has also been successfully used in frictional soils (Ball and O'Sullivan, 1982; Fountaine and Brown, 1959; O'Sullivan and Ball, 1982); in these soils however, measured vane shear strength values include a frictional component due to unknown confining stresses. But the main problem with the shear vane is that the shear strength parameters, cohesion and friction, cannot be separated. However, in this study, the determination of cohesion and friction at zero matric potential received more emphasis than their determination at other moisture contents. This is because of the need to compare directly the contributions which different root densities make to the cohesional and frictional stabilities of the soil samples at the moisture contents at which they are more easily eroded. The shear vane was therefore used mainly in determining shear strength variations with moisture content.

3.4.1 The Vane Experiments

In these experiments, a 19 mm hand-held direct reading shear tester (Serota and Jangle, 1972), with a shear strength measurement range of 0 - 130 kPa, was used to determine shear strength variations with moisture content in samples with different root densities. Other measurements made are moisture content, bulk density and root density.

3.4.1.1 Procedure: The sample is saturated by ponding water on the soil surface for between 30 minutes and 3 hours. On saturation, the ponded water is removed and the measurements made as follows:

i) Vane Shear Strength - the vane is pushed into the top 5 cm of the soil and the torsion head rotated slowly at a constant speed of about one complete rotation per minute (Serota and Jangle, 1972). The torque is registered by the movement of a maximum pointer from a factory set 'zero' to the shear strength value of the soil (kPa) which is read directly from the dial on the torsion head.

ii) Moisture content - the soil sheared by the vane is collected in a drying tin of known weight, weighed, oven-dried for 48 hours at 105°C, weighed and the volumetric moisture content by dry weight calculated (ADAS, 1982; Blake and Hartge, 1986).

iii) Bulk density - Bulk density was determined using the core method (ADAS, 1982). Samples were taken with a minimum of soil disturbance as follows. A thin-walled cylindrical bulk density sampling ring, 4 cm long and about 5 cm in diameter, is pressed vertically into the soil next to where shear strength has been determined. A spatula is then interted below the ring so that an excess of the soil could be withdrawn with the ring. The sampling ring has a removable lid with a small hole which permits trapped air to escape as the container is inserted into the soil; the lid also has space to extend the internal dimensions of the ring by about 10 mm. This prevented the soil from being compressed during sampling whilst allowing some excess soil to protrude at the other end. The excess soil at either end of the ring is then sheared off so that the ring is level full. The soil so collected is weighed, oven-dried for 48 hours at 105°C and re-weighed. The dry weight is divided by the volume of the bulk density ring to give unit-volume dry bulk density. It must be pointed out, however, that this variable was not measured during the sandy clay loam experiments which were done first. This is because at the time it was not considered that roots might have any significant influence on changes in bulk density. However, during the experiments, observations of the behaviour of high root density samples at low moisture contents suggested that it may be useful to investigate dry bulk density changes with the drying of root-permeated soils. Hence bulk density was only determined for the clay samples.

iv) Root density - sampling for root density was done adjacent to the bulk density/shear strength sampling sites. The sample collection procedure was the same as for bulk density. The sample was then washed vigorously in a 250 micron aperture sieve so that all the soil was removed and the roots retained. These were oven-dried for about 10 hours at 105°C and weighed. The dry weight of the roots is then divided by the volume of the soil to give root density (Böhm, 1979).

After the initial measurements have been made at the saturated moisture content state, the sample is left to dry under greenhouse conditions for about 12 hours at a time, so that the soil attains a lower moisture content. The measurements are then repeated at this lower moisture content. In this way, the shear strength, moisture content, root and bulk density are determined at different moisture contents.

3.4.1.2 Data Analysis: Among the variables measured, only bulk density and vane shear strength are related to the moisture content at the time of sampling. All the root density values for a sample box are averaged to give the root density for which the sample bulk density/ shear strength - moisture content variations are determined. For each root-free and root-permeated sample, the bulk density and shear strength values are correlated with the soil moisture contents at time of sampling. This is to determine how the root-free bulk density/ shear strength variations with moisture content are influenced by root density variations.

3.4.2 The Torsional Shear Box Experiments

The NIAE torsional shear box was used in these experiments to determine shear strength at zero matric potential for each sample. Zero matric potential was determined by means of a small mercury tensiometer (Richards, 1965) inserted next to the sampling point (Plate 3.1, also Figure 3.2).

The shear box apparatus consists of a cylindrical metal box about 10 cm in diameter and 5 cm deep. It is fitted with a removable lid which has a 1 sq.cm hole in the centre to accommodate the metal shaft on which a torque meter is mounted (Plate 3.3). On the inside walls of the box there are four equally spaced small fins about 50 mm long, 10 mm wide and 0.8 mm thick; these prevent the soil from slipping relative to the box (Payne and Fountaine, 1952).

3.4.2.1 Procedure: For the vegetated samples, the surface vegetation is first removed by cutting the grass at the base of the shoots. The soil surface is then ponded with water, as in the vane experiments, until the soil's water matric

PLATE 3.3 <u>THE SHEAR VANE AND TORSIONAL SHEAR BOX EQUIPMENT</u>

potential is zero. Matric potential is a dynamic property of the soil which is related to the absorptive forces of the soil matrix (Hanks and Ashcroft, 1980). In theory, in a saturated soil, matric potential is zero. Matric potential is usually determined by means of a tensiometer and it is calculated (Hanks and Ashcroft, 1980; Taylor and Ashcroft, 1972) from:

$$M_p = -12.6\,H_{Hg} + H_o \qquad (3.2)$$

Where: M_p = The matric potential

H_{Hg} = The distance from the top of the mercury column to the surface of the mercury in the container

H_o = The distance from the surface of the mercury in the container to the centre of the porous pot in the soil. (See Sketch Fig 3.2).

Using this relationship, the tensiometer for this experiment was set up so that the height of the surface of the mercury in the container above the centre of the porous pot in the soil, H_o, was 12.6 cm. The matric potential of the soil would therefore be zero when the height of the mercury column in the tube is 1 cm above the level of the mercury in the container (H_{Hg} = 1cm). To make it easy to determine the height H_{Hg}, the plastic tubing in the mercury container was marked off in centimetre divisions.

At zero matric potential, the ponded water, if any, is removed and the sample immediately sheared as follows: the torsional box is forced to its full depth into the soil. The soil surrounding the box is carefully removed, taking care not to disturb the position of the box and

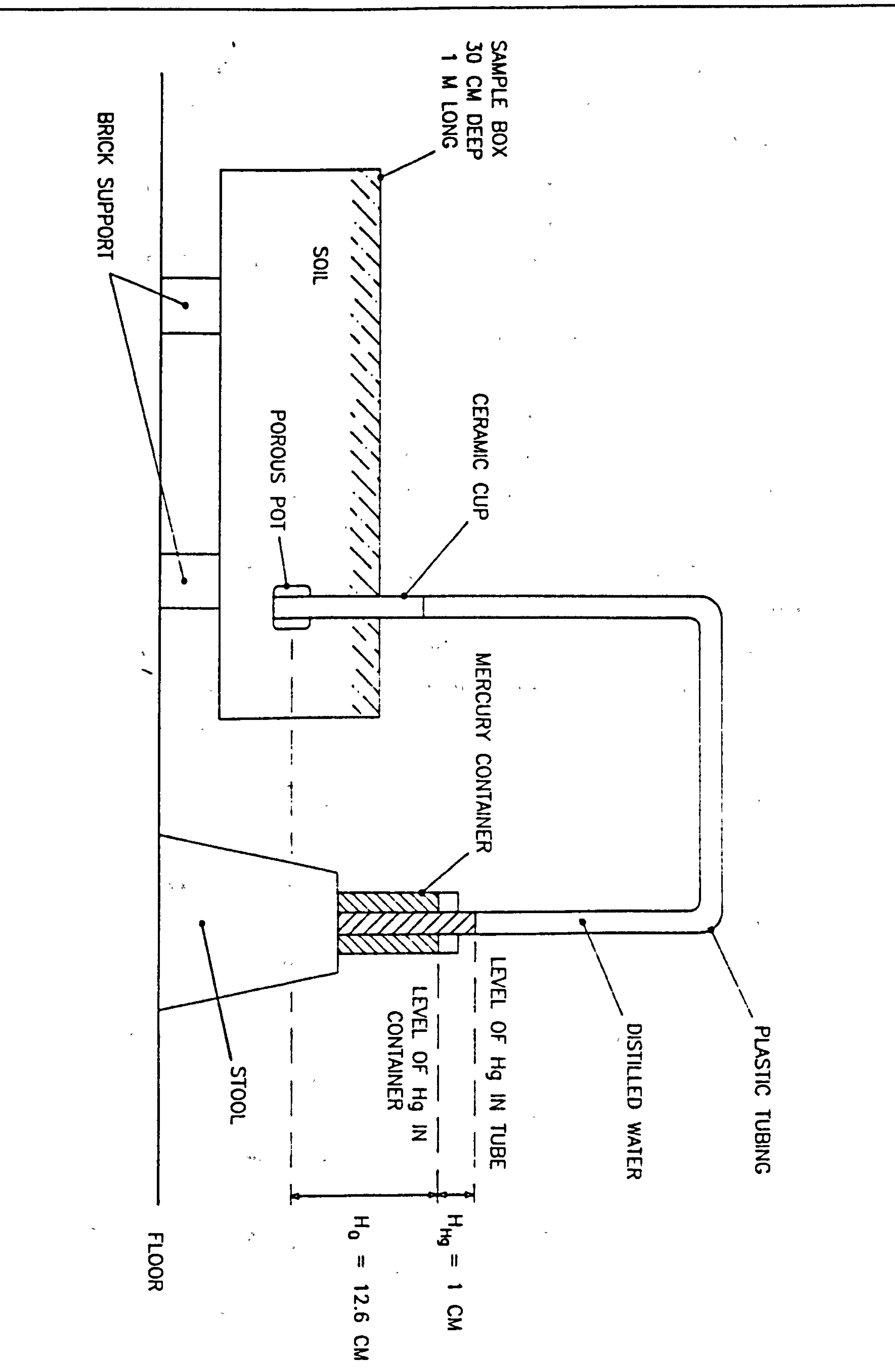


FIG 3.2 : SKETCH OF TENSIOMETER SET UP FOR TORSIONAL SHEARBOX EXPERIMENTS

ensuring that there is no soil-metal friction at the sides of the box. The soil is removed down to a depth of about 3 mm below the bottom of the torsional box to prevent the edges from carrying any of the applied load, but not deep enough to lessen the strength in compression of the short cylinder of soil exposed. The appropriate load is then added to the top of the torsional box. The torque meter and its shaft are mounted in the lid of the box and twisted at a constant speed until the maximum torque is reached at failure; this torque corresponds to the maximum shear strength of the soil. This procedure was carried out at different sampling points in the sample box for "no load" and for small loads (Fountaine and Brown, 1959; O'Sullivan and Ball, 1982) of 5, 10 and 15 Kg (0, 6, 12 and 18 kN/m^2). For each load, the maximum torque obtained is recorded and converted into shear strength from the following simplified equation (Payne and Fountaine, 1952):

$$S = \frac{3M}{2\pi r^3} \qquad (3.3)$$

Where: S = The shear strength (lbs/sq.in)
M = The maximum torque at failure (lbs-ins)
r = The radius of the box (ins)

Two root- and one bulk-density samples are also collected from every sampling point; the average values obtained from them represent the root, and saturated bulk densities of the sample box.

3.4.2.2 <u>Data Analysis:</u> For each root density treatment sample, the computed shear strength values are correlated and regressed on their corresponding normal pressures. The shear strength-normal pressure plots produce an approximately straight line. The intercept value of the resulting regression equation represents the cohesion (C) whilst the slope value represents the angle of soil friction (tan ϕ). Thus for each root density, the shear strength parameters of the Coulomb equation (3.1) are derived.

The effect of root density variations on these parameters at zero matric potential is determined by correlating the derived parameter values with their corresponding root density values. Also, for the saturated soil conditions in which the torsional shear box measurements were made, the undrained clay cohesion (Cu) values, at zero normal pressure, determined for each clay root density treatment sample, are used in bank stability analysis (Gray and Leiser, 1982; Nash, 1987) with a view to determining the effect of root density variations on the stability of the channel bank conditions which the clay experiments simulate.

Two groups of limit equilibrium methods are commonly used for applying soil shear test data to the stability of earth materials (Bache and MacAskill, 1984; Gray and Leiser, 1982; Nash, 1987). They involve the use of either effective stresses (Bishop and Morgestern, 1960) or total stresses (Janbu, 1954; Taylor, 1937). These methods are reviewed by Nash (1987). In the effective stress method, the total stress, σ, in the Coulomb Equation (3.1) is assigned to the stress acting on the soil skeleton (σ^1) and that due to the pore water in the soil (u), so that the effective stress acting on the soil skeleton is given by: $\sigma^1 = \sigma - u$, showing that it is the most critical pore pressure which determines whether failure will take place or not. In order to calculate the in situ effective stress at failure, therefore, the total stress and the pore pressure must be measured simultaneously. However, a limitation of the torsional box shear test method used in this study is that pore pressure and total stress cannot be measured simultaneously (O'Callaghan et al, 1965). To determine pore water pressures in this study it would have been necessary to use disturbed samples (cores) from the sample box in a laboratory triaxial method of shear strength measurement. But as pointed out earlier in paragraphs 2 and 3 of Section 3.4, an overriding consideration in this study is to determine in situ shear strength parameters - an approach for which the torsional shear box is most suitable (Fountaine and Brown, 1959; O'Callaghan et al, 1965; O'Sullivan and Ball, 1982; Schafer et al, 1963). Consequently, the torsional box undrained cohesion values, determined at zero normal pressure, are used (Gray and Leiser, 1982; Nash, 1987) and Janbu's (1954) total stress stability method is adopted in preference to an effective stress approach to determine the effect of root density on the stability of the saturated clay bank conditions simulated by the experiments.

3.5 The Flume Experiments

In these experiments, two sets of measurements were made for the determinations of tractive forces up to the critical tractive force, and flow resistance. For the tractive forces, only depth of flow measurements were needed because the slope of the flume was fixed at about 2^{o} for all the experiments. For the total flow resistance using the Manning's equation (2.3), velocity and depth were measured.

3.5.1 Procedure

The test procedure consisted of passing successive 40-minute measured flows, progressing from low to high discharges, down the test section and making all the observations needed to compute the hydraulic characteristics of the channel. Ten to fifteen minutes were allowed for the flows to attain equilibrium condition before observations were started; during this time, the temperature of the water was determined and the measuring instruments primed. The initial flows were set so that minimum depths of about 10 and 3 mm were attained for flows in vegetation and on bare samples respectively.

For experiments to test the effects of root density on flow characteristics and on scour, all the surface vegetation in the sample box is removed by carefully cutting the grass at the base of the shoots without leaving stumps. The sample box is then lowered into the working section of the flume (Plate 3.2A) and subjected to an initial low flow. If no erosion occurs, the flow is increased, thereby increasing flow depth and velocity (See Section 3.2) until either incipient scour takes place or until the maximum flow capacity of the flume or the flume section is reached. Incipient scour is considered to have occurred when soil dispersal begins and noticeable surface degradation takes place. At this stage, the clear flowing water turned cloudy and became muddy as flow continued. The occurrence of this critical flow condition is further confirmed by subjecting the sample to the next incremental flow higher than the critical; in all cases, the flowing water immediately turned muddy and stayed that way. Observation of the sample after the higher flow indicated the existence of widespread linear scour holes over the surface of the sample. The tractive force of the flow for the critical condition is designated the critical tractive force (CTF) and represents the maximum tractive/ scour resistance of the sample. Similar methods of determining the occurrence of CTF (Dickinson and Scott, 1979; Dunn, 1959; Grissinger et al, 1981; Moore and Masch, 1962; Smerdon and Beasley, 1961) have been criticised because of their subjectivity (Graf, 1971) as compared to more sophisticated approaches such as the use of high speed cinematographic techniques. However, because of its simplicity, the method of determining the initiation of motion through observation is still being widely used (Petit, 1989; Poesen and Torri, 1989), and in these experiments was found to be easily applied, and reproducible. As a result it was possible consistently to determine the relative magnitudes of the critical tractive forces for all the root density samples which were compared. Since the emphasis in these experiments is to evaluate the relative effects of root density increases on CTF, this method of determining the occurrence of CTF was found to be adequate.

For the experiments to test the effects of vegetation density on flow characteristics and scour, a sample box of known vegetation density (number of stands/area of soil) is lowered into the flume and subjected to flows, as was done for the bare soils, until the flow capacity of the flume is reached.

For each test flow, velocity is measured using a velocity meter (Kent Lea Miniflo). Depth of flow was measured using a depth probe, calibrated in millimeters mounted directly above the flume and which can slide across and along the length of the sample box. Measurements were made at 20 cm upstream from the downstream end of the approach box, and at points 25, 50 and 75 cm downstream along the sample box. At each of these positions, measurements were made at three points across the box. These were averaged to give values for the computation of the hydraulic characteristics on the approach slope and on the sample boxes (Chow, 1959; Ree and Palmer, 1949). After each experiment on the bare soils on which CTF was observed, vane shear strength is immediately determined at the three different positions used for hydraulic measurements. In addition, the root density of the sample is determined as described in Section 3.4.1.1.

3.5.2 Data Analysis

From these data, the following hydraulic parameters were computed for each flow on each sample.

i) The Reynold's and Froude numbers: The Reynold's number (Re) was computed from (Chow, 1959; pp 7-8):

$$Re = \frac{VD}{\nu}$$

Where
- V = velocity of flow in feet per second
- D = depth of flow/hydraulic radius
- ν = the kinematic viscosity of the water in ft^2/sec., which, for the flume water at 20^oC is equal to 1.08×10^{-5}.

The Froude number (F) was computed from (Chow, 1959; P13):

$$F = \frac{V}{\sqrt{g.D}}$$

Where
- V = mean velocity in F.P.S.
- g = the acceleration of gravity in ft/sec^2 = (32)
- D = depth of flow in ft.

The computed Froude and Reynold's numbers are used to describe the states and regimes of the flows to which the soils are subjected and to determine how these flow characteristics are influenced by the variations in the grass root and shoot densities.

ii) Manning's n: Manning's retardance coefficient, n, is computed for each flow on the bare root-free and root-permeated soils from the Manning Velocity equation (2.3). The coefficients computed for the root-free and root-permeated soils are designated n_s and n_{rs} respectively. Plots of these n values for each root density against flow depth, at constant channel bed slope (2^o), are used to determine the effect of root density variations on flow velocity retardance. This procedure of describing the hydraulic resistance of channel roughness characteristics is widely used in hydraulic literature (Chow, 1959; Kouwen et al, 1981; Petryk and Bosmajian, 1975;, Ree and Palmer, 1949; Temple, 1982; Thompson and Roberson, 1976; USDA Soil Conservation Service, 1954) and is valid for the uniform flow conditions produced in the experiments whereby for each average flow depth there is a unique mean flow velocity.

For the vegetated samples, the total resistance to flow (n) is also computed for all flows from Equation 2.3. These n values are used to determine the effect of vegetation shoot density on flow retardance.

However, in the vegetated samples, the total flow retardance (n) is due to the root-permeated soil (n_{rs}) and the vegetative elements (n_v), Therefore, by invoking the concept of frictional linearity (Chapter 2.6), the flow retardance of each of these roughness components in the vegetated samples is determined from the relationship $n = n_{rs} + n_v$. Similarly, the retardance due to the roughness of the roots in the soil (n_r) is determined from $n_{rs} = n_r + n_s$. The flow retardance values computed with these relationships are used to determine the tractive resistance of the individual channel roughness components, as explained in the next section.

iii) Tractive/Scour Resistance: The unit tractive force approach is used to estimate the scour resistance of the root density samples. The tractive force Equation (2.2), relates to the force of the flowing water acting on the bed of a channel (Figure 2.1). The distribution of this force along channel boundaries is not uniform but it varies only with the shape of the channel. The various direct and indirect methods that have been used in determining the distribution of tractive force in channel flows are discussed in Chow (1959) and Graf (1971). In general, in a channel of given shape, the tractive force acting on the banks is less than that acting on the bed. Consequently the bed tractive forces determined in the flume experiments need to be translated into bank tractive forces. Graphs of the maximum unit tractive forces that can be expected to act on the banks and beds of rectangular and trapezoidal channel sections have been prepared by the U.S. Bureau of Reclamation for use in channel design (Chow, 1959; Lane, 1953). From these graphs (Chow, 1959; Figure 7 - 7, Page 169), for the rectangular flume channel used in this study, the average maximum unit tractive forces that would be expected to act on banks were estimated to be:

$$TF = 0.73 \quad WDS \qquad (3.4)$$

Where

TF = The tractive force acting on banks, and W, D and S are as defined in Equation 2.2.

This relationship is used in this study to estimate the bank critical tractive forces for the root-free and root-permeated soils. The critical tractive force values are then correlated with the root densities and the shear vane strengths of the samples in order to determine how scour resistance is related to the root densities and to the vane shear strengths.

For the vegetated samples, the tractive forces resisted in each flow by the total channel bank roughness (TTF) are also computed from Equation 3.4. But the tractive forces acting at the soil -

water interface along channel banks are estimated from the Temple (1980) (Equation 2.4), modified such that the parameter C_F is set to zero for reasons discussed in Section 2.6 and n_s is replaced by n_{rs} because the soils of vegetated samples are root-permeated, not root-free. The equation for the tractive force acting at the soil - water interface along channel banks then becomes:

$$TF\ (rs\ or\ s) \;=\; 0.73\ WDS \left[\frac{n_{rs}\ or\ n_s}{n}\right]^2 \qquad (3.5)$$

Where: TF_{rs} = The tractive resistance of the root-permeated soils of vegetated channel banks

TF_s = The tractive resistance of the soils of vegetated channel banks, ignoring the effects of roots.

The other variables are as defined earlier.

From these tractive force data, the following are computed:

The tractive resistance of the vegetation shoots (TF_v) = TTF - TF_{rs} ; the tractive resistance of the roots (TF_r) = TF_{rs} - TF_s. For each flow, in each vegetation density, the values from TF_v, TF_r and TF_s are expressed as a proportion of the total channel tractive resistance (TTF) in order to assess the relative importance of the shoots, roots and soils in resisting scour.

It should be pointed out that although a range of n_s and n_{rs} values exist for each soil tested, it is the maximum n_s and n_{rs} values that are used in these computations. This is because it was desired to determine the maximum tractive resistance that could be contributed by the soil and roots in vegetated channel flows in which the soil has root densities similar to the ones from which the n_{rs} values are derived.

CHAPTER FOUR

THE RELATIONSHIPS BETWEEN SOIL SHEAR STRENGTH AND MOISTURE CONTENT AT VARYING ROOT DENSITIES

4.1 General Trends

This chapter examines the relationship between shear strength and moisture content for root-free and root-permeated samples of a sandy clay loam and a clay with a view to determining the effect of root density. Average shear strength and moisture content values were determined at 7 root densities for the sandy clay loam and 8 densities for the clay. These data are presented in Appendix 4.1. Dry bulk density was determined but only for the clay soils for reasons explained in Section 3.4.1.1., these data are also presented in Appendix 4.1.

It was observed that only the root-free and the 0.2 g/cm^3 root density sandy clay loam values showed both increasing and decreasing shear strength with decreasing moisture content, as has been observed by Nichols (1932) and Ohu et al (1986). All the other samples showed only increasing shear strength with decreasing moisture content. The reasons for this are that the surfaces of the sandy clay loam samples with root densities of 0.5 g/cm^3 and higher became so hard on drying that the shear vane could not penetrate them so no data could be obtained. A similar problem was encountered with clay samples having root densities of up to 1.2 g/cm^3. For the clay samples with higher root densities, an additional problem was that although the vane penetrated the samples at the lowest moisture content shown for them, it could not shear the soils at those moisture contents. These samples were therefore assigned the maxi-possible vane strength value of 130 kPa, with a 'plus' sign to indicate that the actual shear strengths at these moisture contents is certainly greater. Notwithstanding this, the estimated maximum shear strength values were included in the analyses that follow since the results will be used mainly for descriptive purposes. Also, because decreasing shear strength with decreasing moisture content values was found for only a few samples, only data showing increasing shear strength with decreasing moisture content are used for subsequent analyses and discussions.

4.2 Data Analyses

Before determining the relationship between shear strength and moisture content, it was considered necessary to ascertain whether the observed variations in shear strength are significantly different for soils with different root densities and whether these variations are in fact observed within similar ranges of moisture content. Only when this is verified can the effects of the roots on the observed shear strength variations be realistically examined further. Otherwise differences in the observed shear strength variations may be partly or mainly attributable to differences in moisture content. An analysis of variance (Ryan et al, 1985) shows (Table 4.1) with 95% confidence that moisture content variations among the sandy clay loam, and clay samples were not statistically significantly different from each other. This is clearly reflected in the clustering of the mean moisture content values within a narrow range (42 - 50%) for the clay and 16 - 20% for the sandy clay loam, and in the considerable overlaps in the 95% confidence intervals of the sample means, as shown diagramatically in Table 4.1. This implies, therefore, that for each soil, shear strength variations in all samples with different root densities were measured at similar ranges of moisture content. The results in Table 4.2, on the other hand, show that the shear strength variations among sample treatments are significantly different from each other at the 95% confidence level. This is also borne out by the very large variations in the means and their confidence intervals as shown in the confidence interval diagrams (Table 4.2). The mean shear strengths vary widely between 7 and 25.5 kPa for the sandy clay loam samples and between 11 and 44 kPa for the clay samples. These results, taken together, imply that the significant differences observed in shear strength variations among samples can be explained by variations in root density.

Table 4.1:

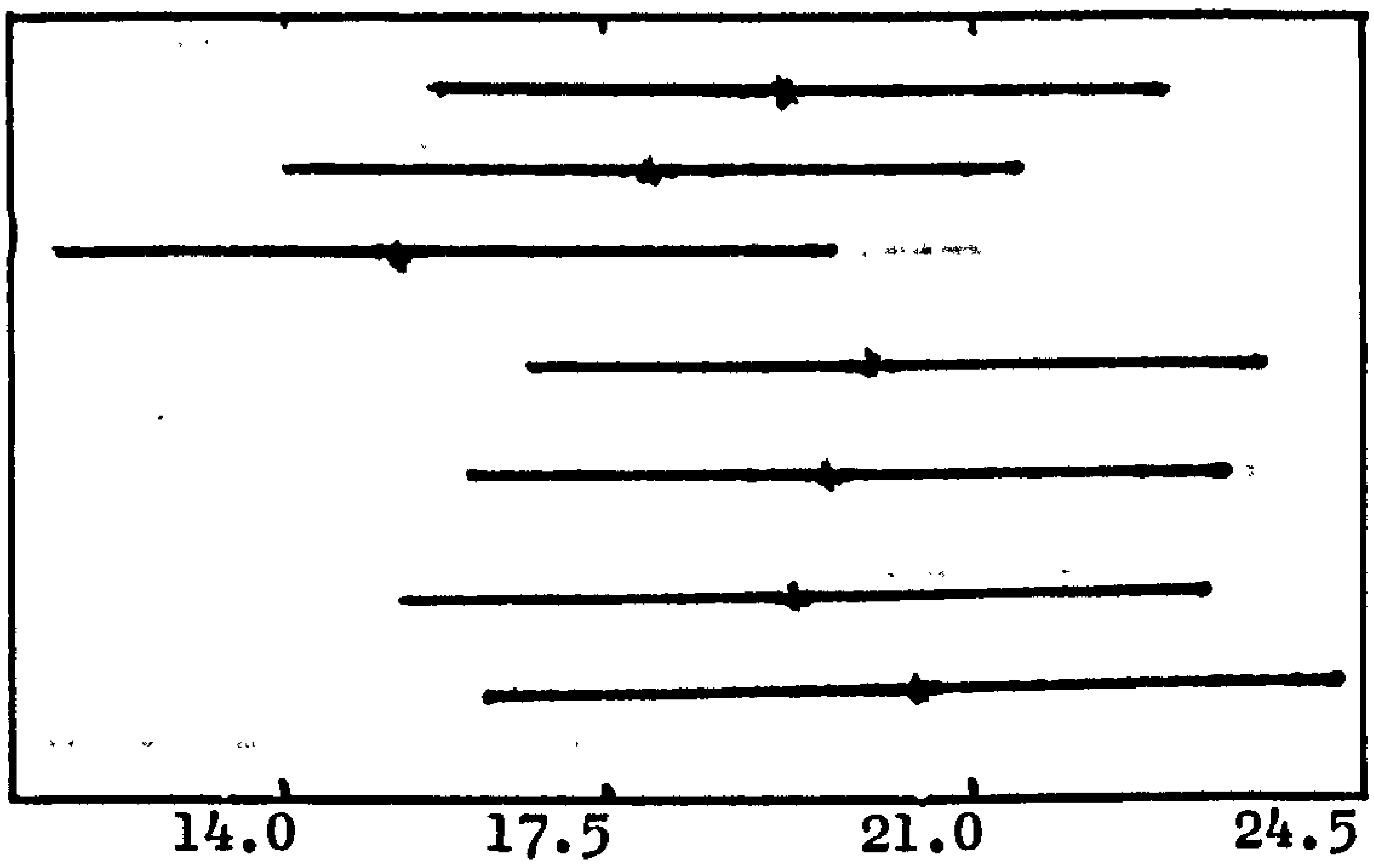
ANALYSIS OF VARIANCE FOR MOISTURE CONTENT VARIATIONS IN ROOT DENSITY SAMPLES

(A) SANDY CLAY LOAM SOIL

Source	DF	SS	MS	Computed F	Table F at 0.05
Among samples	6	295.80	49.3	0.87*	2.19
Within samples	101	5752.90	57.0		

*Not significant at 0.05

95% confidence intervals of Mean moisture content values



(B) CLAY SOIL

Source	DF	SS	MS	Computed F	Table F at 0.05
Among samples	7	849	121	0.55*	2.10
Within samples	107	23764	222		

*Not significant at 0.05

95% confidence intervals of Mean moisture content values

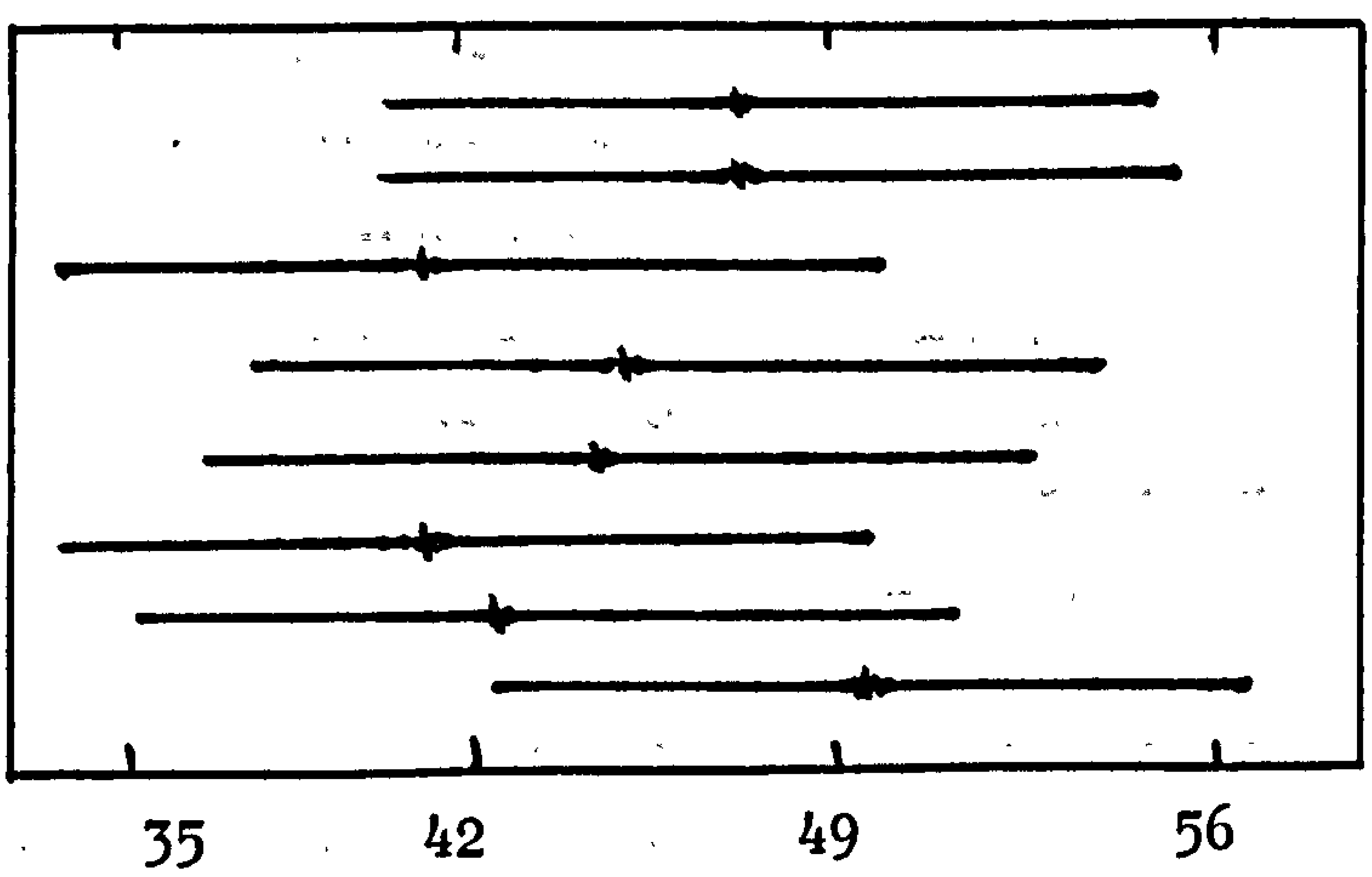


Table 4.2:

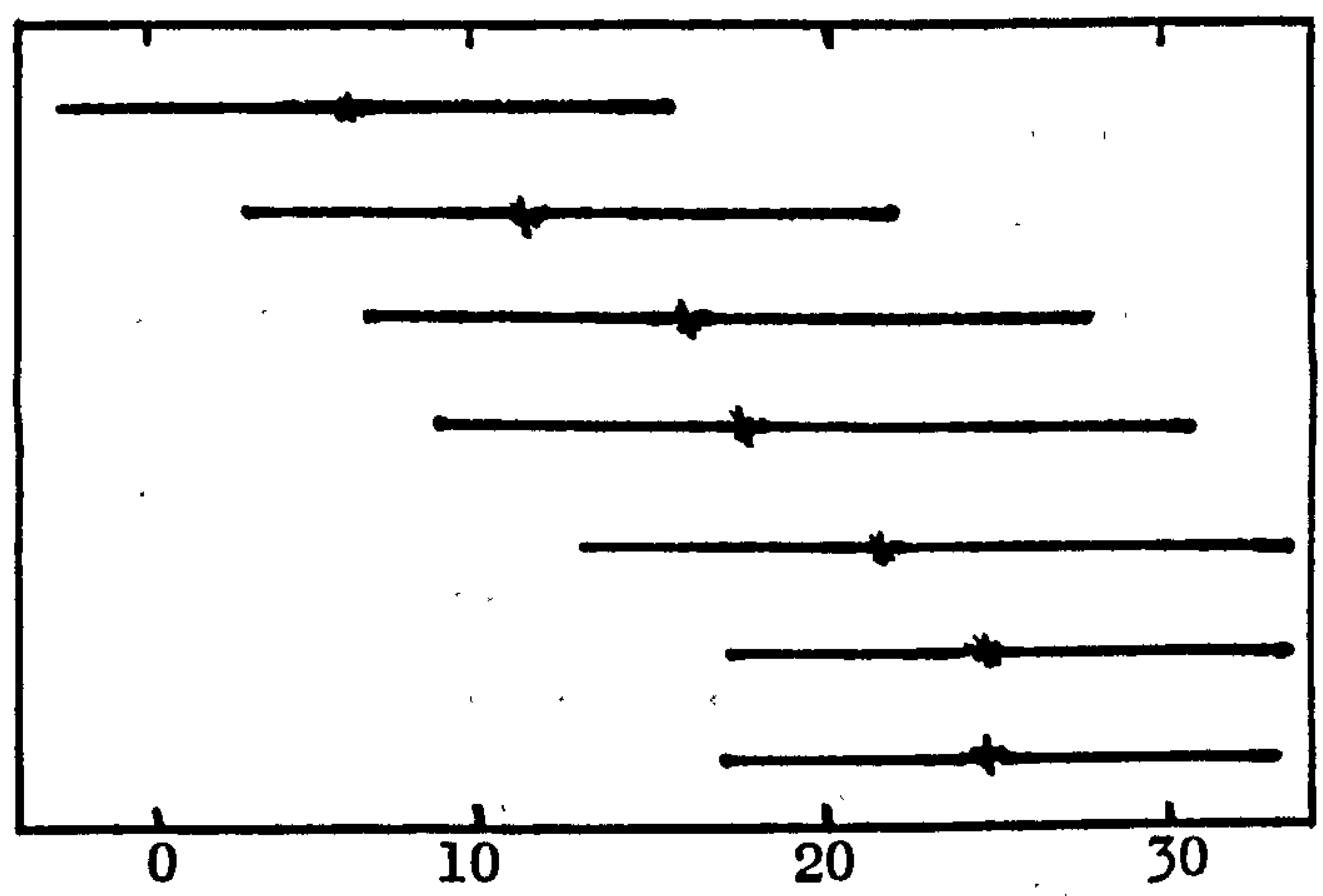
ANALYSIS OF VARIANCE FOR SHEAR STRENGTH VARIATIONS IN ROOT DENSITY SAMPLES

(A) SANDY CLAY LOAM SOIL

Source	DF	SS	MS	Computed F	Table F at 0.05
Among samples	6	4205	701	2.41*	2.19
Within samples	101	29399	291		

*Significant at 0.05

95% confidence intervals of mean shear strength values

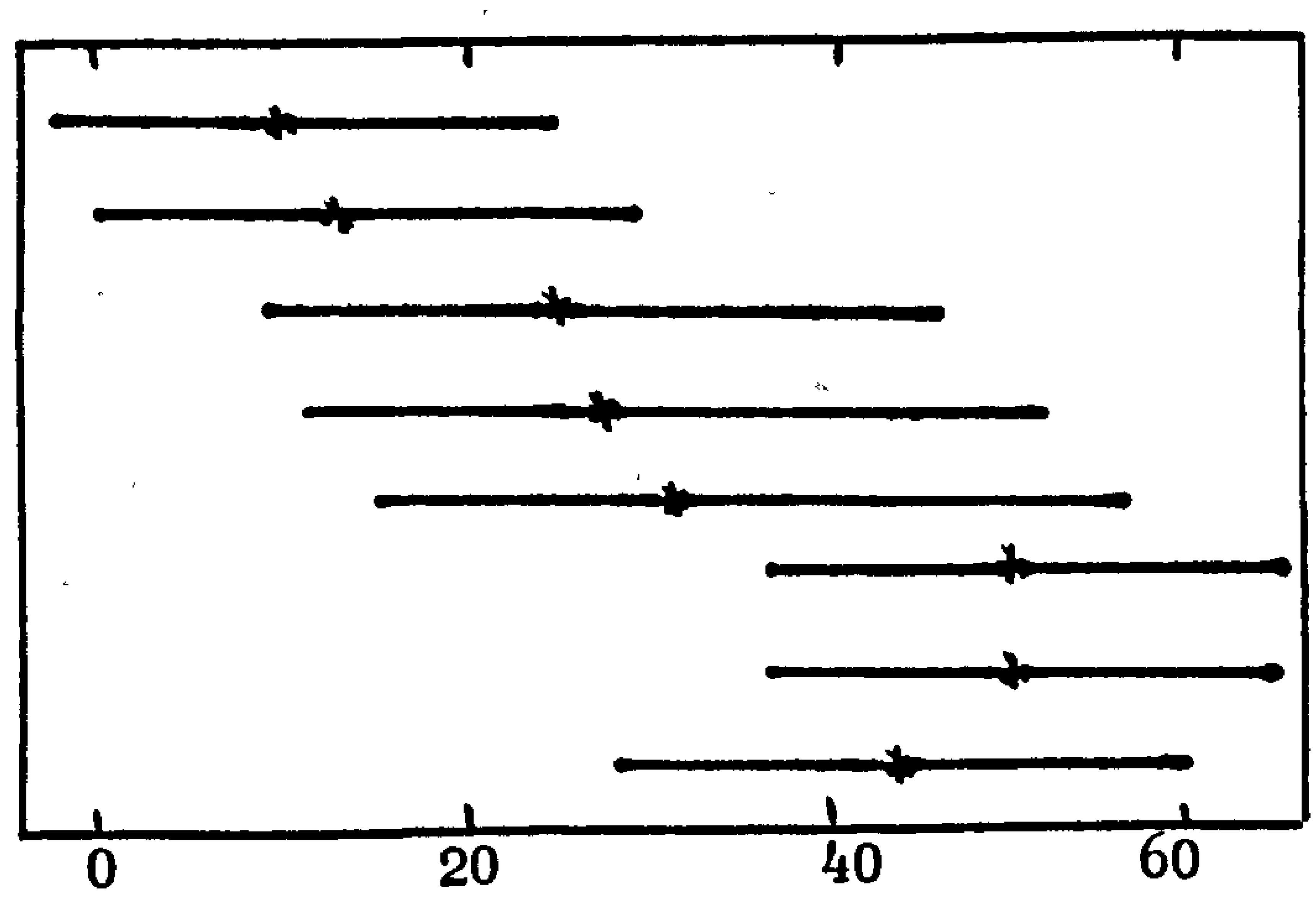


(B) CLAY SOIL

Source	DF	SS	MS	Computed F	Table F at 0.05
Among samples	7	24349	3478	4.37*	2.10
Within samples	107	85074	795		

*Significant at 0.05

95% confidence intervals of mean shear strength values



This possibility was therefore explored by using correlation and regression analyses (Ryan et al, 1985) to determine the nature and degree of shear strength - moisture content relationships for samples with different root densities. As a first step, the extent to which the shear strength and moisture content data satisfy the assumptions of the regression model was ascertained, especially with regard to linearity and the normality of the conditional distributions (Johnson, 1980; Poole and O'Farell, 1971).

The shear strength - moisture content plots showed curvilinear relationships for all samples. To achieve linearity, the shear strength values were transformed using natural logarithm values. The plots, in general, appear linear for all samples although those for the sandy clay loam show better fits than those for the clay samples.

The assumption pertaining to the normality of the conditional distributions was verified using the Minitab Computer Programme on Regression (Ryan et al, 1985). This produced plots of the conditional distributions against moisture content - the independent variable. Plots with very marked trends indicate non-normal distributions of variances whilst plots with no clear trends indicate normal distributions (Ferguson, 1977; Ryan et al, 1985). Examples of typical normal and non-normal plots are shown for two samples in Appendix 4.2. The results showed that for all the root-permeated sandy clay loam samples, the conditional distributions are normal; the plots for the root-free samples indicate only approximate normality. This can be interpreted to mean that the natural log linear regression model adequately explains the shear strength - moisture content variations of the sandy clay loam samples. For the clay samples, however, the conditional distribution of the root-free samples were not normal, and those of the root-permeated samples were only approximately normal. This indicates that the natural log linear regression model only approximately fits the clay shear strength variations with moisture content.

Since this chapter is concerned mainly with an exploration and description of the shear strength - moisture content relationship for samples with varying root densities, correlation and regression analyses were applied to the data of both soils. Shear strength values for each sample were correlated with, and regressed on, corresponding moisture content values in order to describe and quantify the effect of moisture content on shear strength, and to determine the effect of root density on this relationship. Where it is found necessary to investigate further the derived regression parameters either for making estimates, or for making inferences with respect to the underlying relationships or for generalising from the sample data to the soil population from which the samples were obtained, the results for the sandy clay loam soils can be used with much more confidence than those obtained from the clay soil data. The graphs of the shear strength variations with moisture content are shown in Figures 4.1 and 4.2. The correlation and regression parameters and equations describing these relationships are presented in Tables 4.3 and 4.4.

4.3 Discussion of Results

4.3.1 Shear strength variations with moisture content

The graphs in Figures 4.1 and 4.2., and the negative correlation coefficients in Tables 4.3 and 4.4 show that for all the treatments of both soils, shear strength increased with decreasing moisture content. This is to be expected because, at high moisture contents, large amounts of water molecules are adsorbed on the surfaces of the soil particles. These create positive pore water pressures which are high enough to push the soil particles apart and so reduce cohesion and weaken the cementation effects of organic matter and cations that may be present. This reduces the shear strength of the soil to a minimum. On the other hand, at low moisture contents the thickness of the moisture films between particles decreases. This leads to increases in shear strength due to increased suction increasing cohesion (Baver et al, 1972).

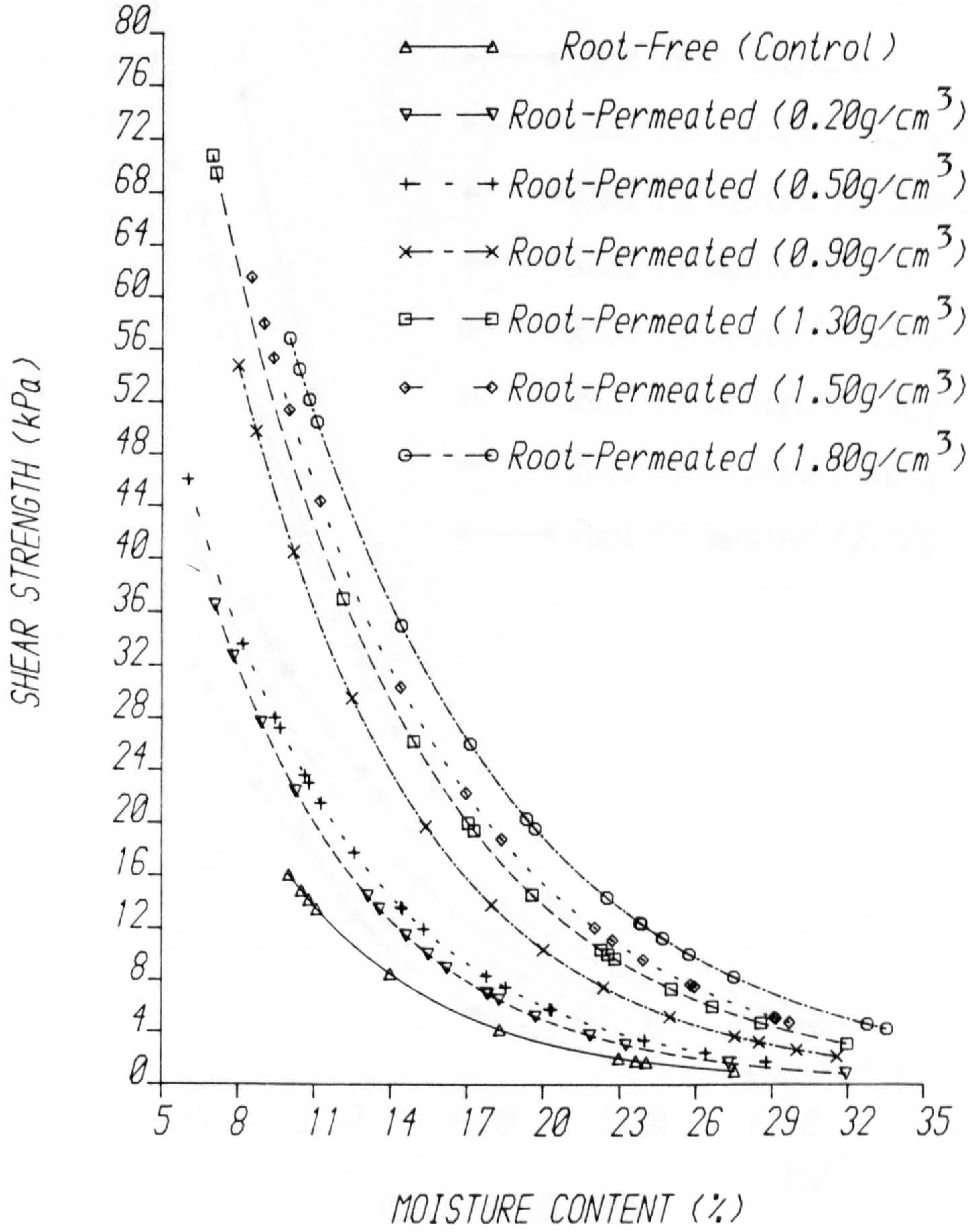


FIGURE 4.1 SHEAR STRENGTH VARIATIONS WITH MOISTURE CONTENT (SANDY CLAY LOAM SOIL)

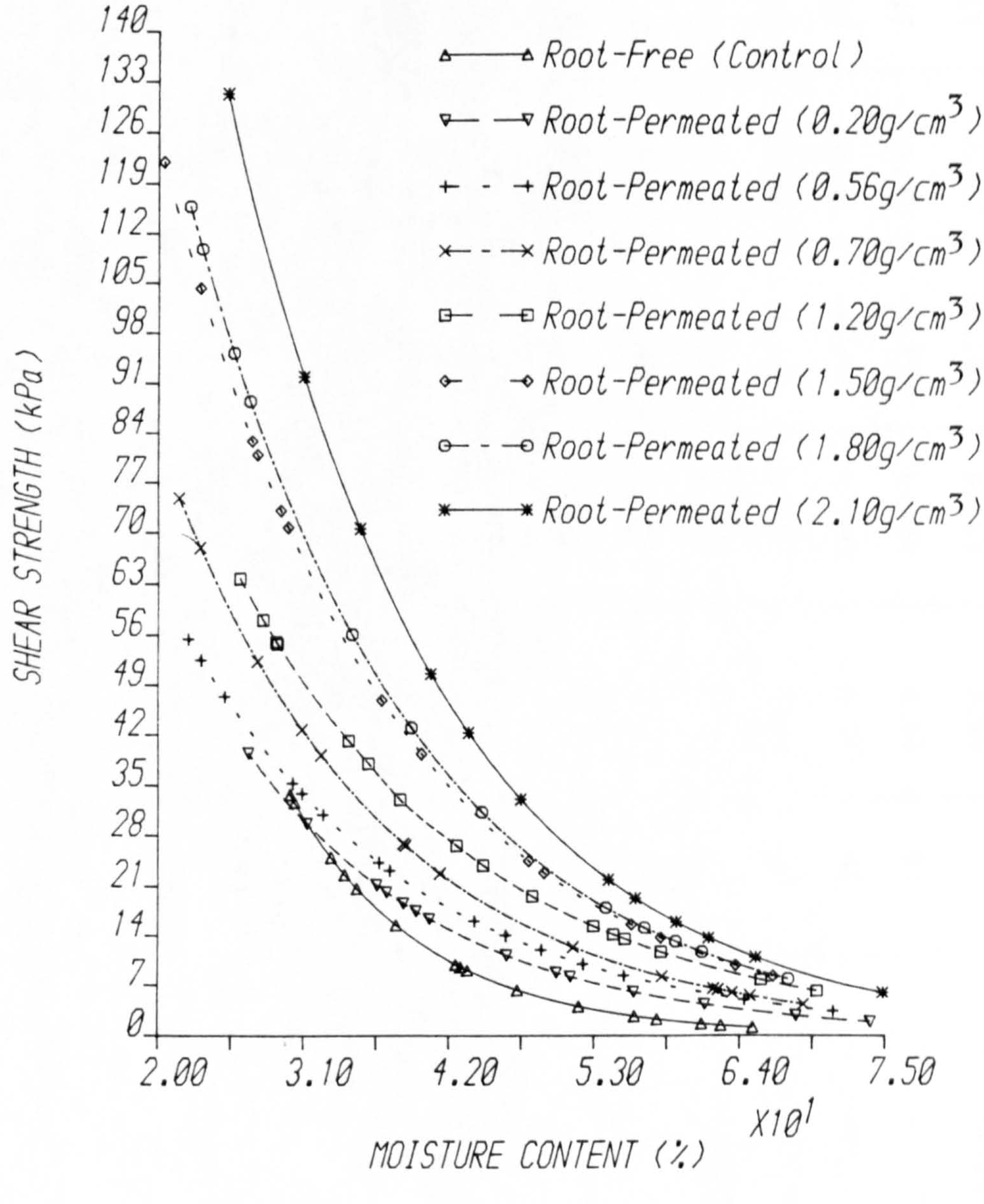


FIGURE 4.2 SHEAR STRENGTH VARIATIONS WITH MOISTURE CONTENT (CLAY SOIL)

TABLE 4.3: CORRELATION AND REGRESSION PARAMETERS AND EQUATIONS FOR THE RELATIONSHIP BETWEEN SHEAR STRENGTH (Y) AND MOISTURE CONTENT (X) (SANDY CLAY LOAM SOIL)

ROOT DENSITY (g/cm^3)	N	r*	b*	SE_b	SEE	r^2%	EQUATION: $Y = ae^{bx}$
Root-Free (control)	11	-0.97	-0.161	0.013	0.26	95	$Y = 80.24e^{-0.161x}$
0.2	17	-0.99	-0.154	0.006	0.16	97	$Y = 108.98e^{-0.154x}$
0.5	18	-0.99	-0.145	0.006	0.14	98	$Y = 110.26e^{-0.145x}$
0.9	13	-0.99	-0.138	0.007	0.19	97	$Y = 165.30e^{-0.138x}$
1.3	14	-0.99	-0.125	0.006	0.15	97	$Y = 168.95e^{-0.125x}$
1.5	16	-0.99	-0.120	0.004	0.11	99	$Y = 170.66e^{-0.120x}$
1.8	16	-0.98	-0.110	0.006	0.16	97	$Y = 171.13e^{-0.110x}$

* Significant at 0.01

TABLE 4.4: CORRELATION AND REGRESSION PARAMETERS AND EQUATIONS FOR THE RELATIONSHIP BETWEEN SHEAR STRENGTH (Y) AND MOISTURE CONTENT (X)

(CLAY SOIL)

ROOT DENSITY (g/cm^3)	N	r*	b*	SE_b	SEE	r^2%	EQUATION: $Y = ae^{bx}$
Root-Free (control)	16	-0.98	-0.097	0.006	0.270	95	$Y = 621.22e^{-0.097x}$
0.20	14	-0.99	-0.064	0.002	0.096	99	$Y = 220.10e^{-0.064x}$
0.56	15	-0.99	-0.057	0.002	0.094	99	$Y = 197.55e^{-0.057x}$
0.70	15	-0.99	-0.060	0.001	0.077	99	$Y = 273.20e^{-0.060x}$
1.20	16	-0.99	-0.053	0.002	0.010	99	$Y = 255.53e^{-0.053x}$
1.50	14	-0.99	-0.058	0.001	0.070	99	$Y = 399.88e^{-0.058x}$
1.80	12	-0.99	-0.059	0.002	0.090	99	$Y = 434.48e^{-0.059x}$
2.10	12	-0.99	-0.062	0.004	0.180	97	$Y = 629.98e^{-0.062x}$

*significant at 0.01

The computed correlation coefficients for these relationships in all samples are all very high, ranging from r =-0.97 for the root-free sandy clay loam samples and r =-0.98 for the root-free clay samples, to r = -0.99 for the root-permeated samples; they are all found to be significant at better than the 95% confidence level. This indicates the existence of a strong inverse shear strength - moisture content relationship. Although in both soils the root-free samples have the lowest correlation coefficients, comparisons (Gomez and Gomez, 1984) show that all the correlations are not significantly different from each other at better than the 99% confidence level. This further indicates that shear strength - moisture content interactions in the root-free samples are not significantly different from those in the root-permeated samples. The corresponding values of the coefficients of determination (r^2) however indicate that about 95% of the observed shear strength variations in root-free samples is associated with concomitant moisture content variations; in the root-permeated samples this moisture content explanation of shear strength variations increases to between 97 - 99% in both soils.

Reference to Figures 4.1 and 4.2 and to the regression equations in Tables 4.3 and 4.4 shows that the observed shear strength - moisture content relationships are exponential indicating that for all the samples tested, increases in shear strength with decreasing moisture content are not uniform throughout the moisture content ranges investigated. From the graphs, it can be observed that at high moisture contents, around the saturation moisture contents of the root-free samples or the liquid limits of the field samples, shear strength increases are small for a small decrease in moisture content. This pattern of behaviour, depicted by the very gentle slopes of the curves at these high moisture contents, is similar in all the treatments of both soils. At low moisture contents, however, the graphs become distinctly steeper, indicating that shear strength increases are large for small decreases in moisture content.

Similar patterns of behaviour have been observed for root-free soils by several investigators including Baver et al (1972), Bjerrum (1950), Chorley (1959), Spoor and Godwin (1979) and Spoor et al (1982b). Baver et al (1972) and Spoor et al (1982b) attributed the behaviour to the shrinkage characteristics of soils. At high moisture contents, when "Structural shrinkage" is said to occur, large amounts of water-loss through drying leads to only a small shrinkage and so to a small increase in shear strength. But at intermediate moisture contents between liquid limit and plastic limit, when "normal shrinkage" occurs, the volume of shrinkage is proportional to the volume of water-loss, thus producing higher rates of shear strength increases for similar decreases in moisture contents.

The average rates of increase of shear strength with moisture loss are given by the exponential regression coefficients (b) in Tables 4.3 and 4.4. These coefficients are all small but significant at better than the 99% confidence level, and have very low standard errors (SE_b). This indicates a small but stable and significant increase in shear strength for a unit decrease in moisture content. The regression coefficients of the relationships for the clay samples are significantly higher, at the 95% confidence level (Gomez and Gomez, 1984), than those for the sandy clay loam samples. This means that shear strength increases for a unit decrease in moisture content are significantly greater in the clay than in the sandy clay loam soils. Since the percentage of clay-sized particles is considerably higher in the clay (54%) than in the sandy clay loam (13%), the clay exhibits greater shrinkage and possesses greater adhesive forces and hence a higher rate of shear strength increase with drying than the sandy clay loam.

Also, for each soil, the regression coefficients show a general increase in magnitude with root density (Tables 4.3

and 4.4). This implies that the rate of shear strength increase with soil drying, increases with root density. For the clay soil, the trend in Table 4.4 shows that initial increases in root density up to 1.2 g/cm^3 are accompanied by increases in the rate of shear strength increase with drying. Subsequent increases in root density result in apparently decreasing rather than the expected increasing rate of shear strength increase with drying. The reasons for this are not immediately apparent. But it was pointed out in Section 4.1 that, for the three highest clay root density samples, some shear strength values that were approximated because of measurement problems were used in the analysis that yielded the regression coefficients being discussed. It now appears that these values were most certainly underestimates and so their use in the analysis has resulted in the underestimation of the regression coefficients for the samples. It is therefore suggested that the last three regression coefficients in Table 4.4 may not represent the actual hebaviour of the soil samples for which they were derived. However, if, notwithstanding these observations, the pattern of behaviour depicted in Table 4.4 is characteristic of this clay soil, then the reasons for it need further investigation.

However, slow rates of soil drying are known to cause higher shear strength increases because they cause a closer packing of soil particles, than faster rates of soil drying (Baver et al, 1972; Gerard et al, 1966). Although it was observed that the surfaces of root-free samples dried out faster than the surfaces of the vegetated samples, this study did not specifically investigate the effect of root density on the rate of soil drying. Consequently it can only be suggested that higher rates of shear strength increase with soil drying are observed for higher root density samples, partly because increases in root density lead to a slower rate of soil drying mainly as a result of the effect of higher surface shading from the higher vegetation covers that would be expected to be associated with the higher root densities. In addition, increasing root density leads to an increase in the surfaces onto which soil particles bond by adhesion. Since the adhesion forces increase with drying, this process could also significantly increase the rate of shear strength increase with soil drying.

It should be pointed out that the intercept values of the equations in Tables 4.3 and 4.4 do not have any real interpretational meaning; they do not indicate shear strength values for zero moisture content conditions for all samples. This is mainly because, as Figures 4.1 and 4.2 show, such moisture content conditions were not investigated.

The results discussed so far indicate that the pattern of shear strength variations with moisture content is similar in the root-free and root-permeated samples of both soils used in this study. However, there are two differences among samples in this relationship which are also important to this study. They are differences in the magnitudes of shear strength at all the moisture contents investigated, and differences in the magnitudes of the rates of shear strength increase with soil drying. Since the main difference in the samples used in this investigation is in their treatment with different root densities, it is concluded that the observed differences in the behaviour of each soil are mainly due to the varying root densities of the treatment samples.

4.3.2 The Effect of Root Density on Shear Strength Variations With Moisture Content

From Figures 4.1 and 4.2, it could be seen that the magnitude of shear strength, as it varies within the range of moisture contents investigated, is least in the root-free samples and increases in samples with increasing root densities. For instance, at and above the saturation moisture contents of the sandy clay loam (30%) and clay (70%), the root-free samples possess no measurable vane shear strength. But in the root-permeated samples, measurable strengths were achieved even in samples with the lowest root density investigated (0.2 g/cm^3), with the magnitude of this strength increasing in samples with increasing root densities. In the sandy clay loam, these increases ranged from about 1.0 kPa in samples with 0.2 g/cm^3 of roots, to 5 kPa in samples with 1.8 g/cm^3 of roots (Figure 4.1). The roots thus increased shear strength, relative to the root-free samples, by at least 500%. In the clay samples (Figure 4.2), a higher relative increase of up to about 850% is achieved in samples with a root density of 0.8 g/cm^3.

Waldron (1977) has reported similar but lower relative shear strength increases of between 96 and 420% for one year old alfalfa plant roots in silty clay loam - gravel soil columns which were at zero matric potential. However the comparison cannot be taken further because the root densities for which these shear strength increases were obtained are not known and, in any case, the increases were for lignified roots of shrubs. Nevertheless, these results indicate that at high moisture contents, increases in the root density of the soils can lead to considerable increases in shear strength resistance. The reasons for this may be that, at these high moisture contents, when the positive pore water pressures are high enough to cause minimum strengths in root-free soils, the roots in the root-permeated soils increase shear strength by reinforcing the soil, thus increasing its cohesion, and by providing surfaces onto which soil particles adhere. Adhesion of soil to root surfaces was observed when washing the root density cores; much more effort was expended in washing clay soil particles than sandy clay loam particles from the roots. Root growth activities of the loretta grass used in this study are known to exude organic and other substances around their root surfaces after only 6 weeks or less of growth (Reid and Goss, 1981). These root exudates are known to bind certain cations very strongly (Mench et al, 1988). Greenland et al (1961, 1962), Oades (1978) and Reid and Goss (1981) have suggested that the exudates from roots can stabilise soils. Reid and Goss (1981) have also observed quantities of soil particles firmly attached to the mucilage secreted around rye grass roots that have been gently washed in water. It is therefore suggested that these organic root exudates cause soil particles to adhere firmly to root surfaces and thus increase the strength of the soil-root matrix. An increase in root density can therefore be expected to increase the magnitude of the root-strengthening effects of these processes.

Figures 4.1 and 4.2 also show that maximum shear strengths were observed in the root-free samples at moisture contents below which the strengths of the root-permeated samples of both soils continued to increase. In the root-free sandy clay loam, for instance (Figure 4.1), a peak strength of about 16kPa was achieved at the plastic limit of the field samples (10% moisture content). In the clay (Figure 4.2), a peak of about 30 kPa was achieved at about 29% moisture content, which is 96% of the plastic limit of the field soils (30% Moisture content). Below these moisture contents, the strengths of the root-free samples decreased whilst those of the samples with even the lowest root density of 0.2 g/cm^3 continued to increase. Unfortunately, the moisture contents at which peak shear strengths occur in most of the root-permeated samples could not be determined because of the problems discussed in Section 4.1.

Nevertheless, these results could be interpreted to mean that as the root-free soils dry out to below plastic limit, cohesion decreases because there is not enough water present to cause the formation of water films around interparticle contacts. This causes the root-free soils to be very friable and so exhibit a decrease in shear strength. In root-permeated samples, on the other hand, the reinforcement and adhesion effects continue to increase and so increase the shear strength of these soils. These results could imply that the commonly held view that the peak shear strength/cohesion of a soil occurs at or very close to the plastic limit (Baver et al, 1972; Nichols, 1932) may not apply to root-permeated soil conditions; here, peak shear strengths occur at moisture contents well below the plastic limit of the root-free soils.

The observed differences in the magnitudes of shear strength were further investigated by determining, through correlation and regression analyses, how root density variations were related to shear strength variations at saturation moisture content and, for comparison, at the plastic limit of the field soils. The shear strength and root density data used in the analyses are presented in Appendix 4.3; the graphs are shown in Figures 4.3 to 4.6, and the regression parameters and equations describing these graphs are presented in Table 4.5.

The graphs in Figures 4.3 and 4.4 and the correlation coefficients of $r = 0.996$ (sandy clay loam) and $r = 0.098$ (clay soil) in Table 4.5, show that, at saturation, there is a strong, positive and linear association between the shear strengths and root densities of both soils. These relationships are significant at the 99% confidence level. The slopes of the equations describing these relationships, which are also significant at 0.01, show that a unit increase in root density (g/cm^3) is associated with an average shear strength increase of about 2.6 kPa for the sandy clay loam, with that for the clay soil being almost double at 4.49 kPa. The coefficients of determination (r^2) indicate that most of the observed shear strength variations, 99.2% in the sandy clay loam and 92.4% in the clay,

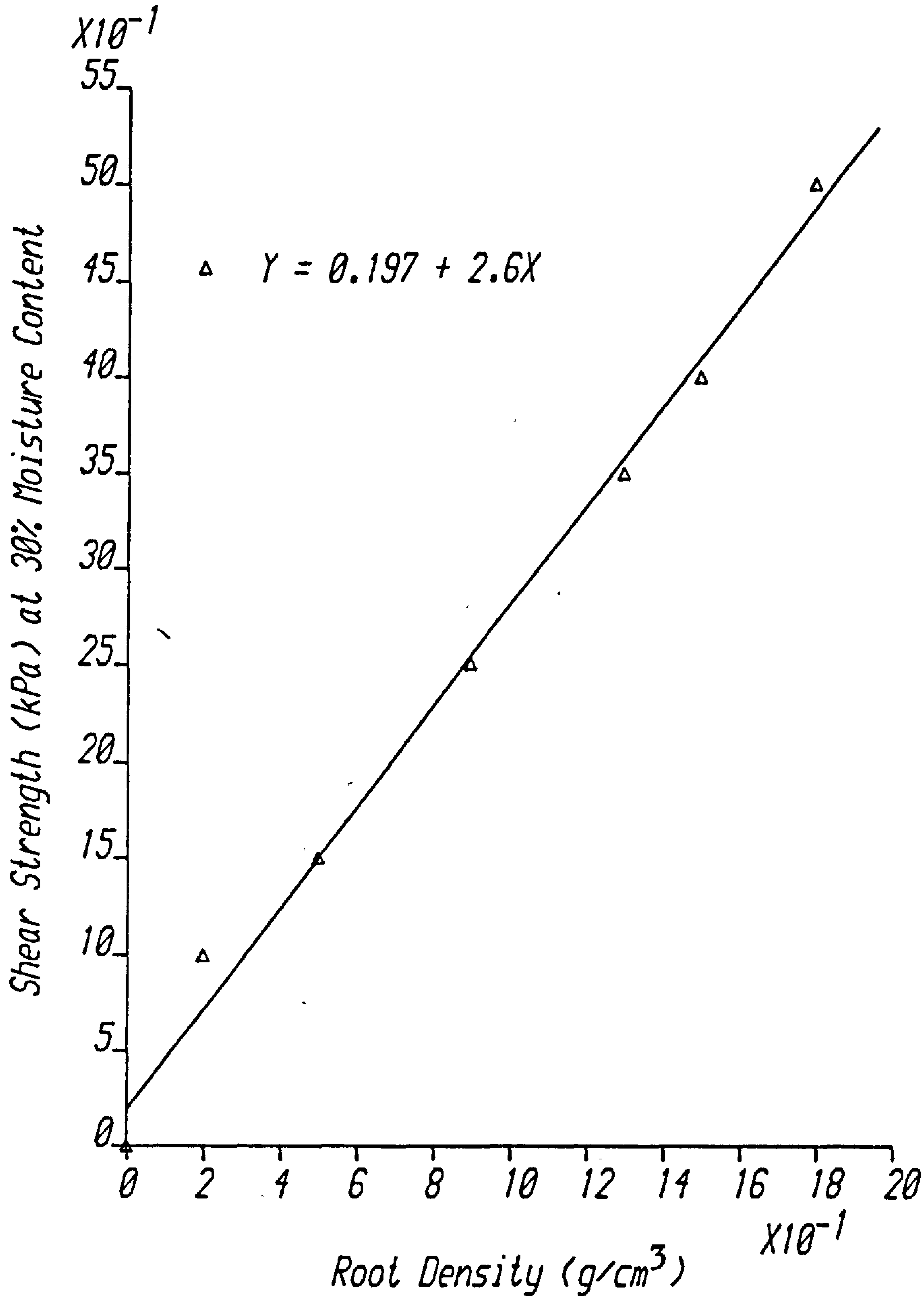


FIGURE 4.3 THE RELATIONSHIP BETWEEN ROOT DENSITY AND SHEAR STRENGTH AT SATURATION - SANDY CLAY LOAM

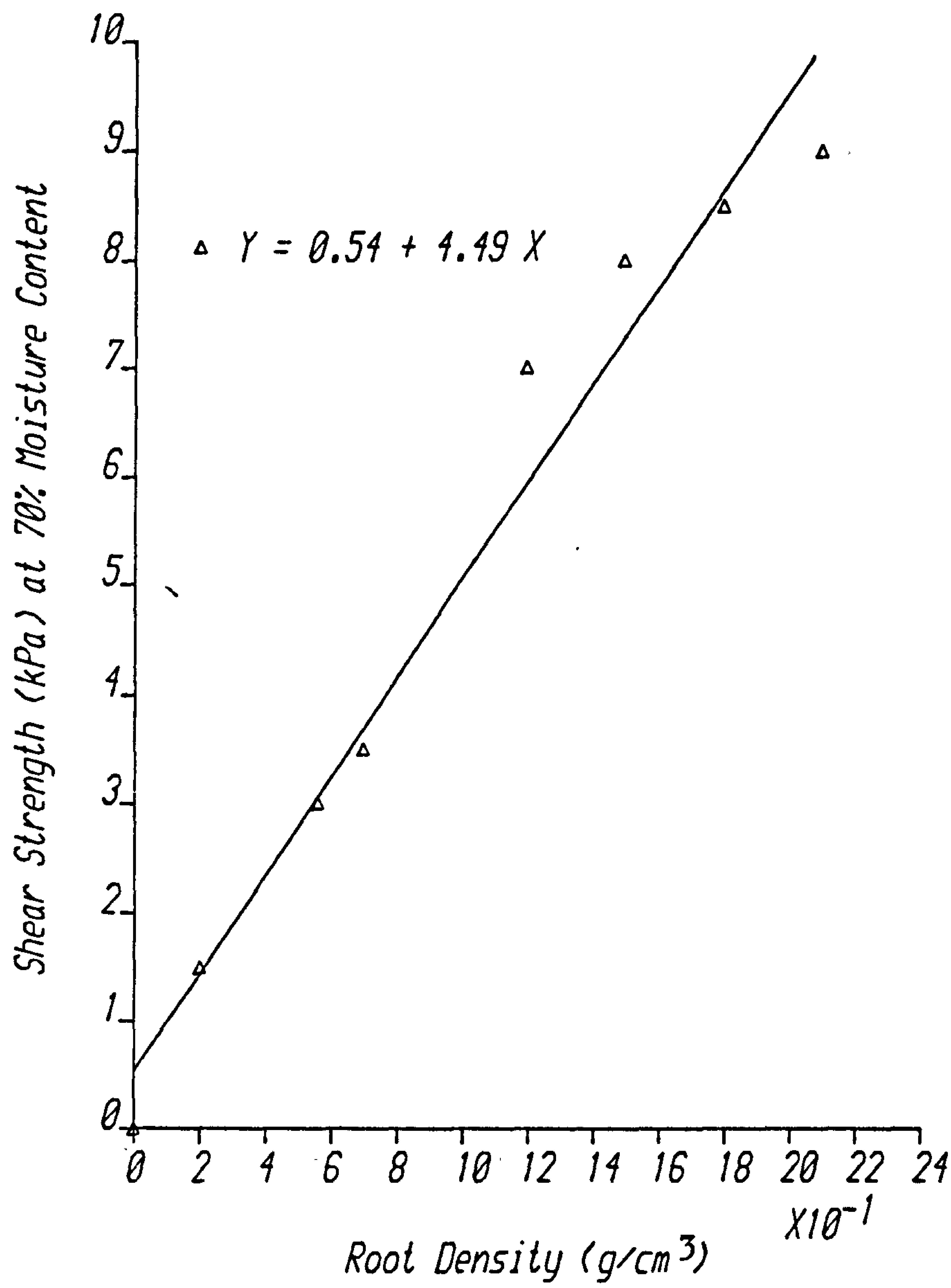


FIGURE 4.4 THE RELATIONSHIP BETWEEN ROOT DENSITY AND SHEAR STRENGTH AT SATURATION - CLAY SOIL

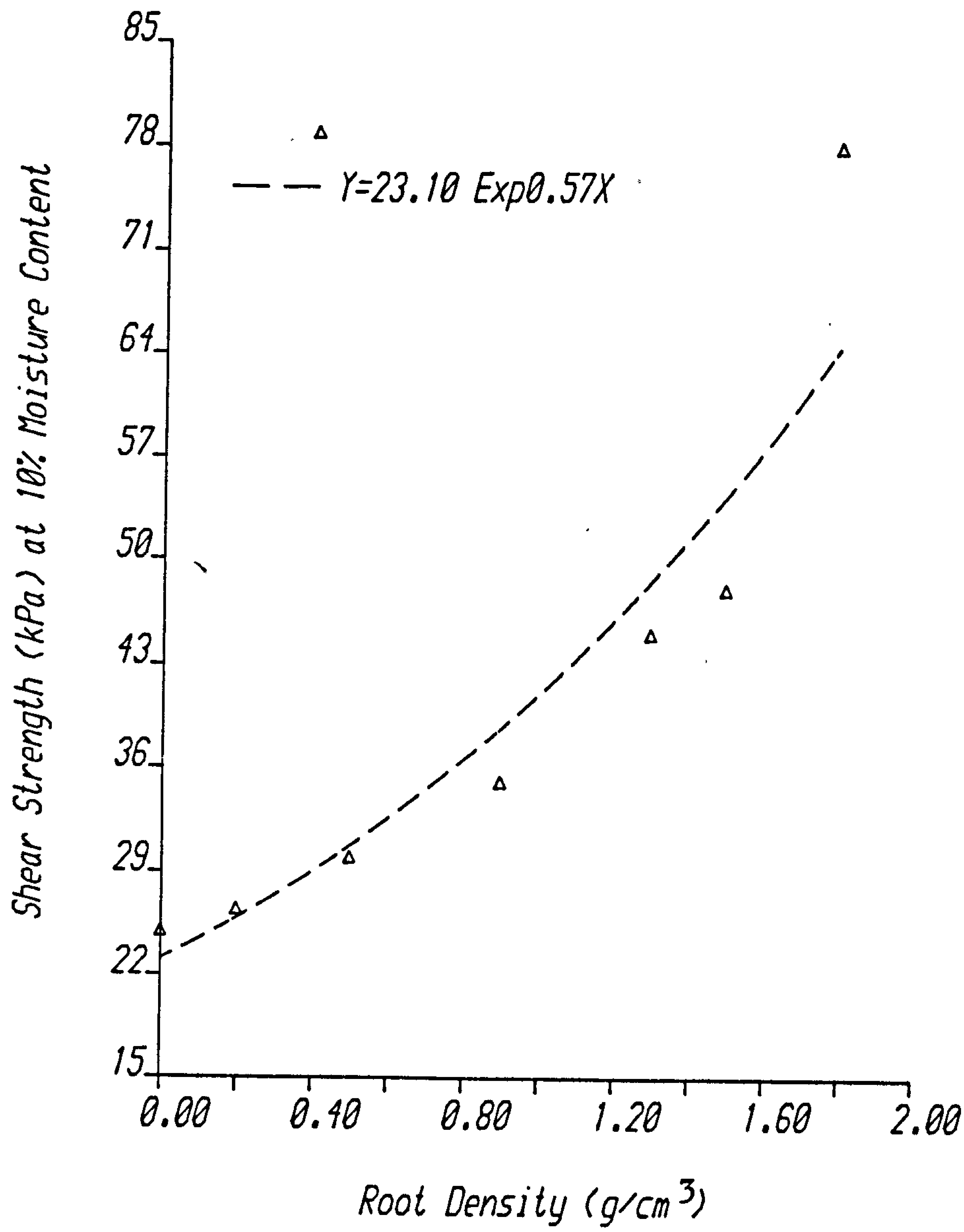


FIGURE 4.5 : THE RELATIONSHIP BETWEEN ROOT DENSITY AND SHEAR STRENGTH AT PLASTIC LIMIT - SANDY CLAY LOAM

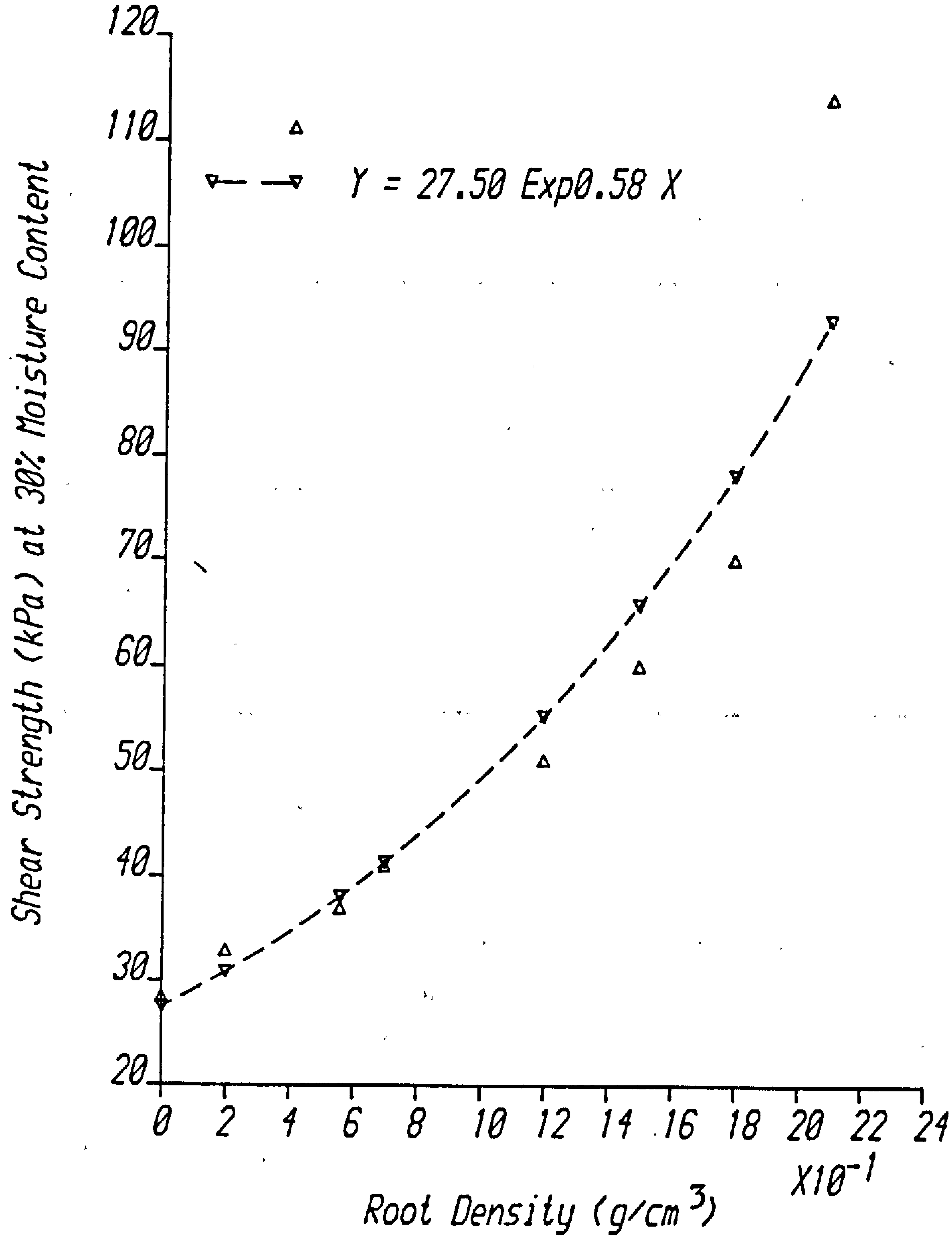


FIGURE 4.6 THE RELATIONSHIP BETWEEN ROOT DENSITY AND SHEAR STRENGTH AT PLASTIC LIMIT - CLAY SOIL

TABLE 4.5:

CORRELATION AND REGRESSION PARAMETERS AND EQUATIONS FOR THE RELATIONSHIPS BETWEEN SHEAR STRENGTH (Y) AND ROOT DENSITY (X) AT SATURATION AND PLASTIC LIMIT MOISTURE CONTENTS

SOIL	N	r*	b*	EQUATION
SANDY CLAY LOAM				
At Saturation	7	0.996	2.60	$Y = 0.197 + 2.6x$
At plastic limit	7	0.961	$e^{0.57}$	$Y = 23.10e^{0.57x}$
CLAY SOIL				
At saturation	8	0.98	4.49	$Y = 0.54 + 4.49x$
At plastic limit	8	0.97	$e^{0.58}$	$Y = 27.50e^{0.58x}$

*Significant at 0.05

can be explained in terms of root density increases. These results therefore show that, at saturation, when the shear strength of root-free soils is minimal, increasing the root density in these soils can greatly increase the shear strength and hence their stability.

At the plastic limits of these soils, however, the effect of root density on shear strength increases is different. Figures 4.5 and 4.6 show logarithmic rather than linear relationships. The graphs show that increases in root density at low density values produced relatively lower shear strength increases compared to root density increases at higher root density values. For instance, increasing clay root densities from root-free to 0.6 g/cm^3 produced shear strength increases of about 8 kPa; a similar increase in root density from 0.6 to 1.2 g/cm^3 produced an almost double (14 kPa) increase in shear strength (Figure 4.6). Similar behaviour is depicted for the sandy clay loam soils (Figure 4.5). The relationships in both soils have high correlation coefficients which are significant at the 0.01 level. This implies that these shear strength - root density relationships at plastic limit can be accepted for both soils with 99% confidence.

The observed difference in the nature of the shear strength - root density relationships at saturation and plastic limit moisture contents would suggest either that the mechanisms by which increases in root density produce increases in shear strength in these soils are different at the two moisture contents or alternatively, the mechanisms operate differently at the two moisture contents. The coefficients of determination for these relationships indicate that, for the sandy clay loam, a lower percentage of shear strength variations can be accounted for by root density increases at plastic limit than at saturation (92.4% compared to 99.2%); for the clay soil, however, the difference is minimal (94.0% compared to 96.5%). From these results, it would seem that as the root-permeated sandy clay loam dries out to the plastic limit, factors other than, or in addition to, the cohesion and adhesion effects of root density increases also cause an increase in shear strength. It was pointed out in Section 4.1 that as the high density root -permeated samples dry out, it was difficult for the vane to penetrate their surfaces. It may be the case that on drying, these soils become so closely bound together by the roots that the frictional strength and hence the bulk density of the soils increase considerably. In such a situation, the forces resisting vane penetration may be produced by the closely packed soil particles and also by the bulk strength of the roots, which would increase with root density, and so make vane penetration even more difficult. It is therefore suggested that at this lower moisture content, the reinforcing effect of the roots is also to increase the bulk density of the sandy clay loam soils. In the clay, a similar reinforcing effect of the roots would probably occur, but in this case, it is suggested that the process is counteracted by the large differential contractions of clays which occur on drying. Evidence of this was observed as the drying root-permeated soil samples cracked and exposed numerous fully tensed roots which were apparently resisting the differential contractions of the soil.

The effect of root density on soil bulk density, either for soil drying or for any moisture content status, is not known. However, from the observations discussed above, it would seem that, for the sandy clay loam soil, the observed shear strength increases with root density at plastic limit are due mainly to increases in cohesion, adhesion and bulk density whilst for the clay, they are due mainly to increases in cohesion and adhesion effects. Similar differences in shear strength effects have been suggested by Camp and Gill (1969) for bulk density variations between 15 and 0% moisture content for root-free Lloyd clay on the one hand, and a silty clay loam and a silt on the other. Comparing the behaviour of the root-permeated soils at saturation and at plastic limit therefore, it seems that for the sandy clay loam, the root density effects causing increases in shear strength are similar in nature but have greater magnitudes at the plastic limit than at saturation. For the clay soil, it would seem that shear strength increases at saturation are due to increases in bulk density, cohesion and adhesion but that at plastic limit, higher magnitudes of cohesion and adhesion are the main root density effects causing shear strength increases, with bulk density effects being minimal.

4.3.3 The Effect of Root Density on Dry Bulk Density Variations With Moisture Content

The bulk density and moisture content data analysed in this section are presented in Appendix 4.1. Since moisture content variations also influence bulk density variations, the moisture content data were first analysed by the analysis of variance technique (Ryan et al, 1985) to determine whether the moisture content variations within which the dry bulk densities were measured were similar among the different root density samples. The results shown in Table 4.6 indicate that moisture content variations among samples are not significant at $P < 0.05$. This provides a statistical evidence that bulk densities were measured in samples that did not have significantly different moisture content variations.

The bulk density values were also analysed in order to determine whether sample bulk density variations were significantly different from each other. Only when such a difference is established, would it be necessary to investigate further how root density variations influence the bulk densities of the samples. The results of the pair-wise Mannwhitney U-test for bulk density variations between samples (Ryan et al, 1985) are presented in Table 4.7.

The results show that root-free bulk density variations are not significantly different from variations in samples with 0.2 g/cm^3 of roots at the 95% confidence level. Comparing the samples for each of these two conditions with those for the other root density treatments, shows significant bulk density variations in both cases. This implies that in these soils, root densities need to be raised to a minimum of 0.56 g/cm^3 before bulk density variations with soil drying will be significantly different from those observed in root-free

TABLE 4.6: ANALYSIS OF VARIANCE FOR MOISTURE CONTENT VARIATIONS IN ROOT DENSITY SAMPLES - CLAY SOIL.

Source	DF	SS	MS	Computed F	Table F at 0.05
Among Samples	7	1933	276	1.60*	1.60
Within samples	51	8811	173		

*not significant at $P < 0.05$

95% confidence intervals of mean moisture content values

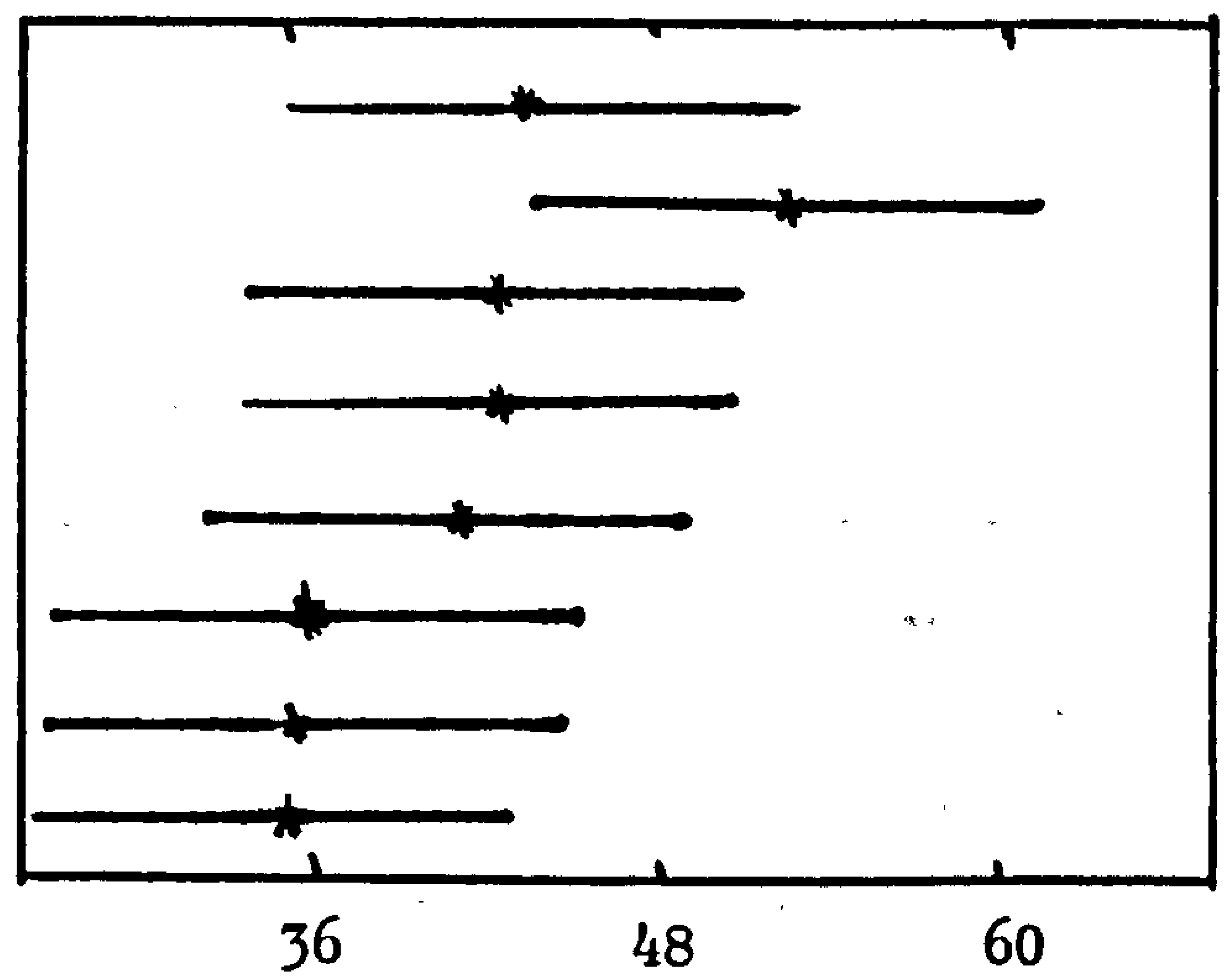


TABLE 4.7: MANNWHITNEY U-TEST FOR DIFFERENCES IN DRY BULK DENSITY VARIATIONS BETWEEN ROOT DENSITY SAMPLES

Sample Root Densities (g/cm^3) Compared	Significance at 0.05
Root-free and 0.20	Not significant
Root-free and 0.56 to 2.10	Significant
0.20 and 0.56 to 2.10	Significant
0.56 and 0.70 to 2.10	Not significant
0.70 and 1.2 to 2.10	Not significant
1.20 and 1.5 to 2.10	Not significant
1.50 and 1.8 to 2.10	Not significant
1.80 and 2.10	Not significant

samples. The results further show that pair-wise comparisons between samples with root densities from 0.56 g/cm^3 to 2.10 g/cm^3 indicate no significant differences in bulk density variations with soil drying. This is interpreted to mean that increasing root densities in these clay soils from 0.56 to 2.10 g/cm^3 is not accompanied by significant increases in bulk density variations with soil drying.

However, since bulk density values and their variations with moisture content in root-free soils are found to be significantly different from those of most of the root-permeated samples, correlation and regression analyses were used to determine the bulk density - moisture content relationships for different root density samples. The graphs of these relationships and the statistical constants and equations describing them are presented respectively in Figure 4.7 and Table 4.8. The graphs show that, as for root-free soils (Camp and Gill, 1969; Spoor and Godwin, 1979), bulk density linearly increases with soil drying in all treatment samples. The high correlation coefficients (Table 4.8), which are all significant at $P < 0.05$, further confirm the linearity of these relationships. The graphs also show that bulk densities are generally higher in root-permeated than in root-free samples. Among the root-permeated samples, however, there is no regular increase in bulk density with increasing root density. The general pattern of bulk density change that emerges from these graphs is that bulk density increases with root density up to 0.56 and 0.7 g/cm^3 of roots. Bulk density then decreases with further increases in root density.

Bulk density is conventionally defined as the mass (weight) of a unit volume of dry soil (Blake and Hartge, 1985; Brady, 1974; Smith, 1981); this volume includes mainly soil solids and pores. Root-permeated soils are however composed of not only solid soil particles, but also of roots which are of

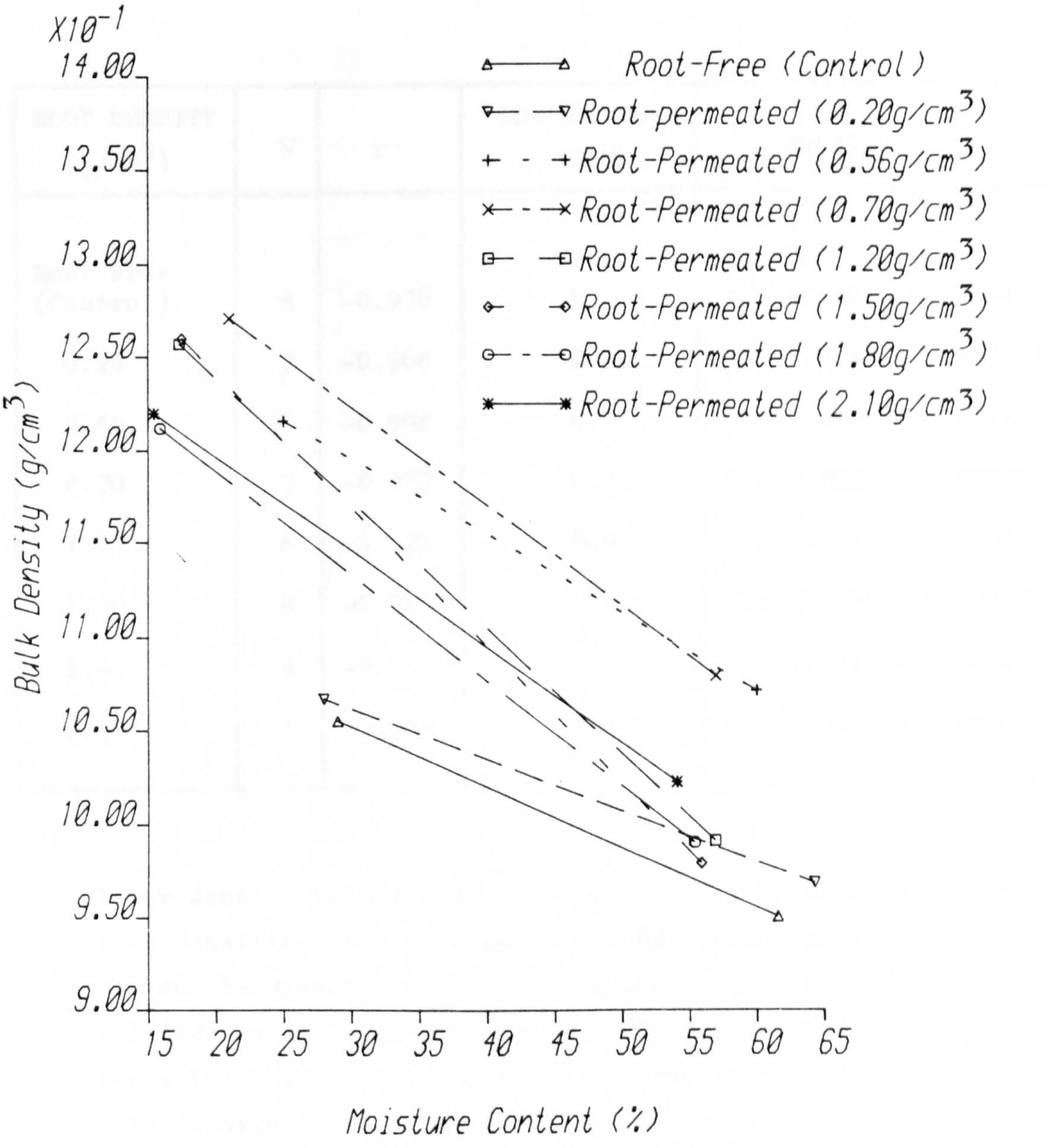


FIGURE 4.7 DRY BULK DENSITY VARIATIONS WITH MOISTURE CONTENT (CLAY SOIL)

TABLE 4.8: CORRELATION AND REGRESSION PARAMETERS AND EQUATIONS FOR THE RELATIONSHIP BETWEEN BULK DENSITY (Y) AND MOISTURE CONTENT (X) - CLAY SOIL

ROOT DENSITY (g/cm^3)	N	r	SIGNIFICANCE LEVEL	EQUATION
Root Free (Control)	8	-0.976	0.01	Y = 1.148 - 0.0032X
0.20	7	-0.968	0.01	Y = 1.2128 - 0.00379X
0.56	6	-0.998	0.01	Y = 1.3184 - 0.0041X
0.70	7	-0.957	0.01	Y = 1.382 - 0.0053X
1.20	8	-0.921	0.01	Y = 1.373 - 0.0067X
1.50	8	-0.983	0.01	Y = 1.388 - 0.0073X
1.80	8	-0.984	0.01	Y = 1.301 - 0.0056X
2.10	7	-0.984	0.01	Y = 1.299 - 0.0051X

lower density relative to soil particles. In soils with low root densities, the very small proportion of roots to soil may not be significant to cause a decrease in bulk density relative to the root-free soils. But as the proportion of roots increases, it is possible to observe a decrease in bulk density in the high root density soils relative to the lower root density soils. This is because the weight contributed by the volume of roots will be significantly lower than would have been contributed by an equal volume of solid soil particles; in addition, the increased volume of roots would increase the volume of pores in the soil. This would cause a further decrease in the weight of a given volume of soil. The decrease in bulk density observed in the high root density samples may therefore be due to the low weight contribution by roots and the increased volume of pores in the samples.

4.4 Summary of Findings

The results of the shear strength variations with moisture content have shown that for both root-free and root-permeated soils, shear strength increases, as expected, with decreasing moisture content; the relationship is found to be exponential in all cases. The results also show that whereas the shear strength of root-free soils decreases with soil drying around the plastic limit moisture content, the shear strength of the root-permeated soil continues to increase at considerably lower moisture contents. It is also found that increases in root density not only considerably increase the magnitude of shear strength at all the moisture contents but also increase the rate of shear strength increase with soil drying. The pattern of shear strength increase with root density at saturation is found to be linear whilst at the plastic limit it is found to be logarithmic. It is suggested that for the sandy clay loam, the difference is due mainly to the increased magnitude of the root density effects of cohesion, adhesion and bulk density at the plastic limit. For the clay, it is due to increases mainly in the magnitudes of the root density effects of cohesion and adhesion; bulk density increases are probably negligible at the plastic limit because of the counteracting effects of differential contractions which occur in drying clays.

The clay dry bulk density variations with moisture content have indicated that root density increases do not affect the pattern of increasing bulk density with soil drying commonly observed for root-free soils. It is however found that increases in root density to about 0.7 g/cm^3 would increase the magnitude of the dry bulk density but that further increases in root density actually lead to decreases in bulk density values.

CHAPTER FIVE

THE EFFECT OF ROOT DENSITY ON SHEAR STRENGTH PARAMETERS

5.1 Introduction

One of the findings reported in Section 4.3.2 is that, at saturation, the magnitude of the shear strength of both soils investigated increases with increasing root density. But because shear strength was determined by the shear vane, it is not clear whether the shear strength increases observed were due to increases in cohesion or angle of soil friction or both. Consequently, the torsional shear box experiments were carried out in order to determine the effect of root density on the cohesional and frictional strengths of the soils, as represented by the Coulomb equation (3.1); this was done however only at the zero matric potential of the soils because of the difficulty of using the torsional box at drier soil moisture contents.

5.2 Data Analyses

Shear strength values at 0, 6, 12 and 18 kPa normal pressures were determined for 16 sandy clay loam root-density samples and for 11 clay root-density samples. As explained in Section 3.4.2.2, from these data, shear strength - normal pressure regression equations were derived to yield estimates of the cohesion and friction values for each root-density sample. The increase in each parameter value at any root density was determined by subtracting the parameter value estimated for the root-free samples from that estimated for the root-density sample. These data are summarised in Appendix 5.1.

In order to determine whether the derived regression equations correctly describe the shear strength - normal pressure relationships observed at all root densities, the estimated cohesion values yielded by the regression equations were correlated with the cohesion values as determined with the torsion box at zero normal pressure.

Similarly, the estimated friction values were compared with the averages of the friction values calculated from Equation 3.1, using the shear strength values measured at 6, 12 and 18 kPa normal pressures. The results, presented in Appendix 5.2, show that the regression equations are a good representation of the observed shear strength variations with normal pressure at all root densities although in both soils, cohesion was better predicted than friction. In order to determine the effect of root density on the estimated shear strength parameters of each soils, the increases observed in the parameter values of the root-permeated samples were regressed on their corresponding sample root densities. The results are shown in Figures 5.1 to 5.4.

5.3 Discussion of Results

5.3.1 The Effect of Root Density on Soil Cohesion

The shear strength - normal pressure data in Appendix 5.1 show that, at zero matric potential, the maximum shear strength of root-free sandy clay loam and clay soils respectively, can be estimated from the Coulomb equations

$$S\ (\text{kPa}) = 1.96 + 0.58\sigma \qquad (5.1) \quad \text{and}$$

$$S\ (\text{kPa}) = 3.58 + 0.117\sigma \qquad (5.2)$$

These equations show that the root-free cohesion values are 1.96 and 3.58 kPa for the sandy clay loam and clay soils respectively.

Much lower root-free cohesion values have been reported by Endo and Tsuruta (1968) and Waldron (1977). Waldron's cohesion value of 2.3 g/cm^2 (0.23kPa) was obtained using a direct shear device at moisture contents similar to those used in this study but for columns of a silty clay loam -

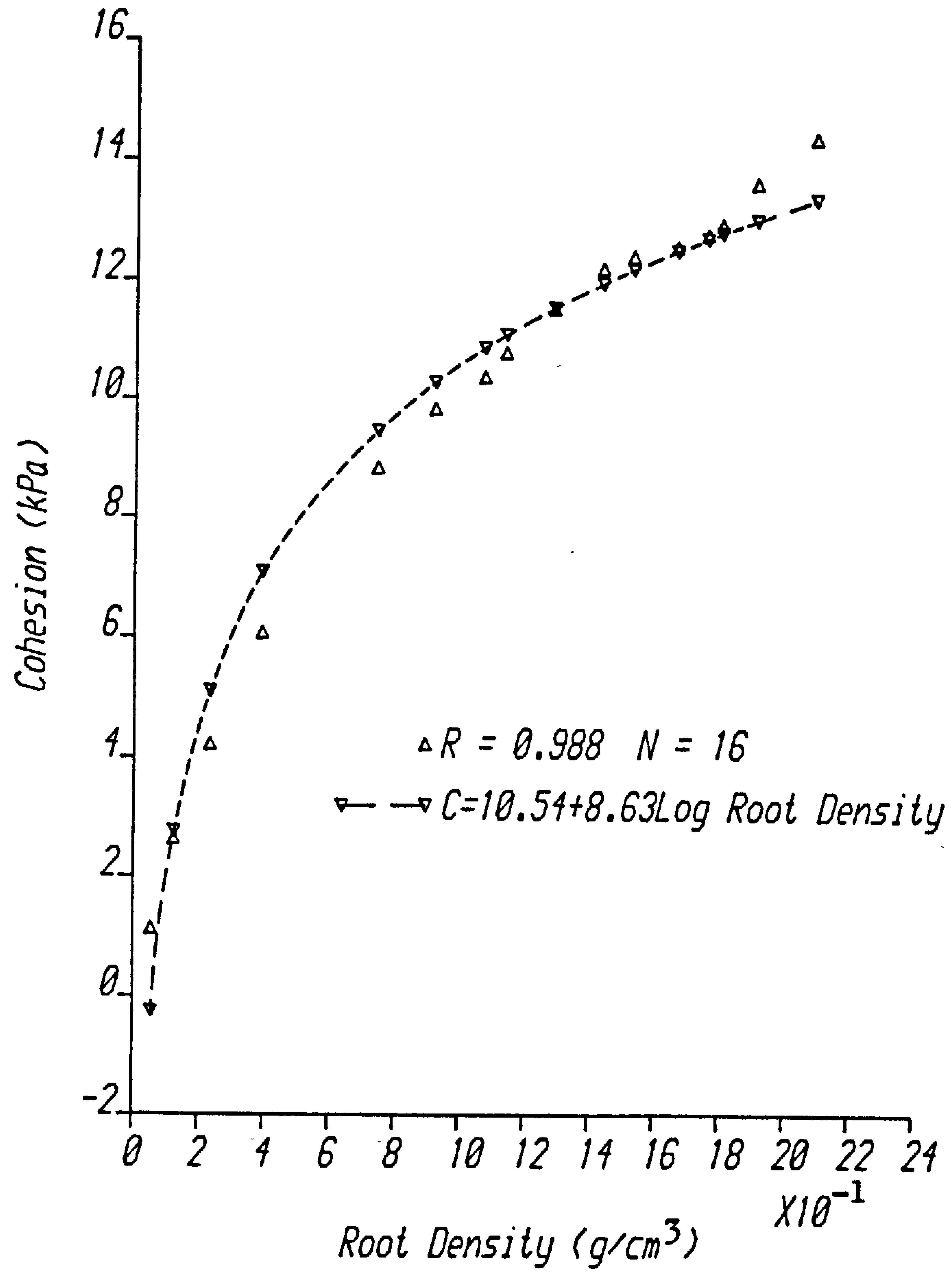


FIGURE 5.1 THE RELATIONSHIP BETWEEN ROOT DENSITY AND COHESION (SANDY CLAY LOAM)

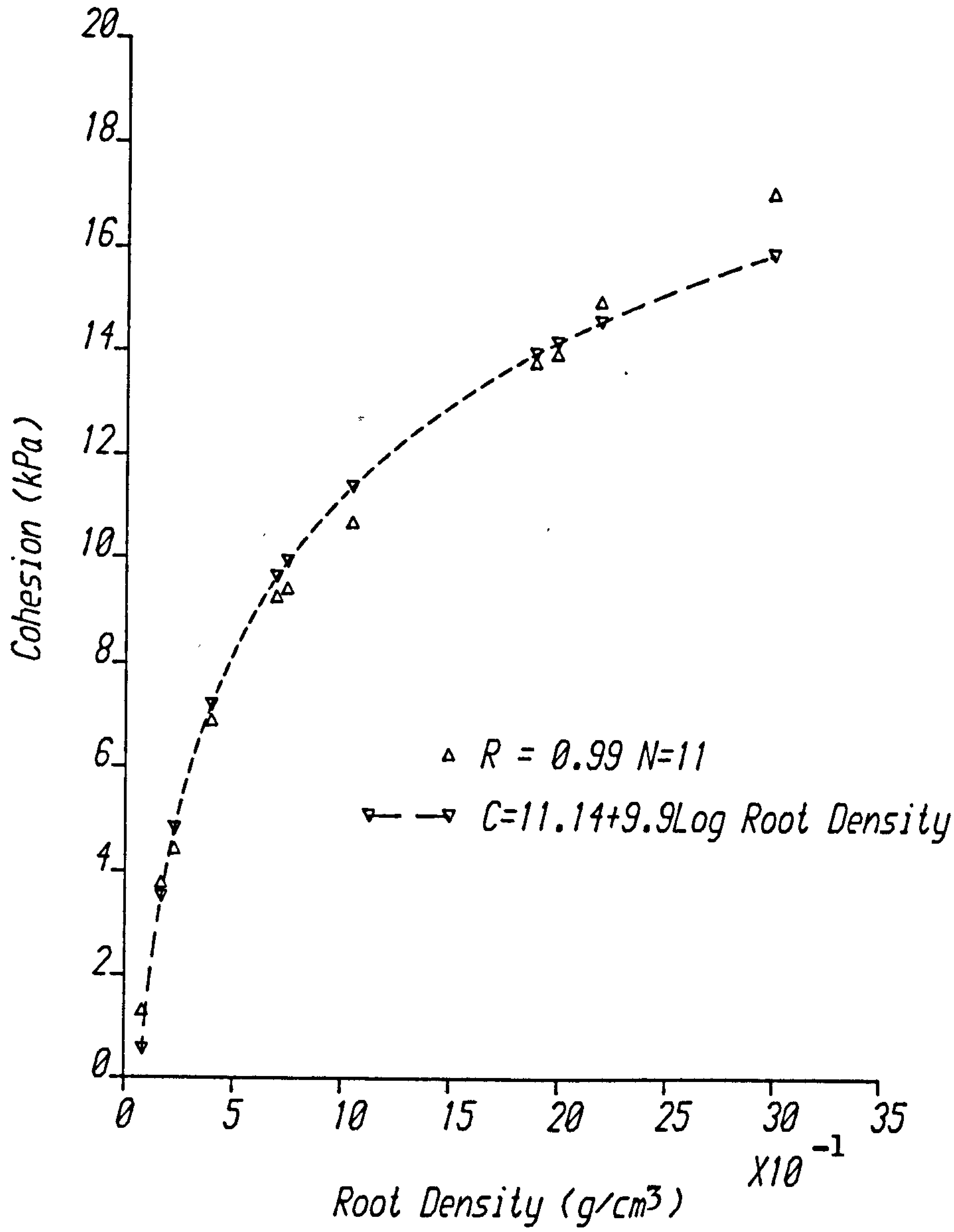


FIGURE 5.2 <u>THE RELATIONSHIP BETWEEN ROOT DENSITY AND COHESION (CLAY SOIL)</u>

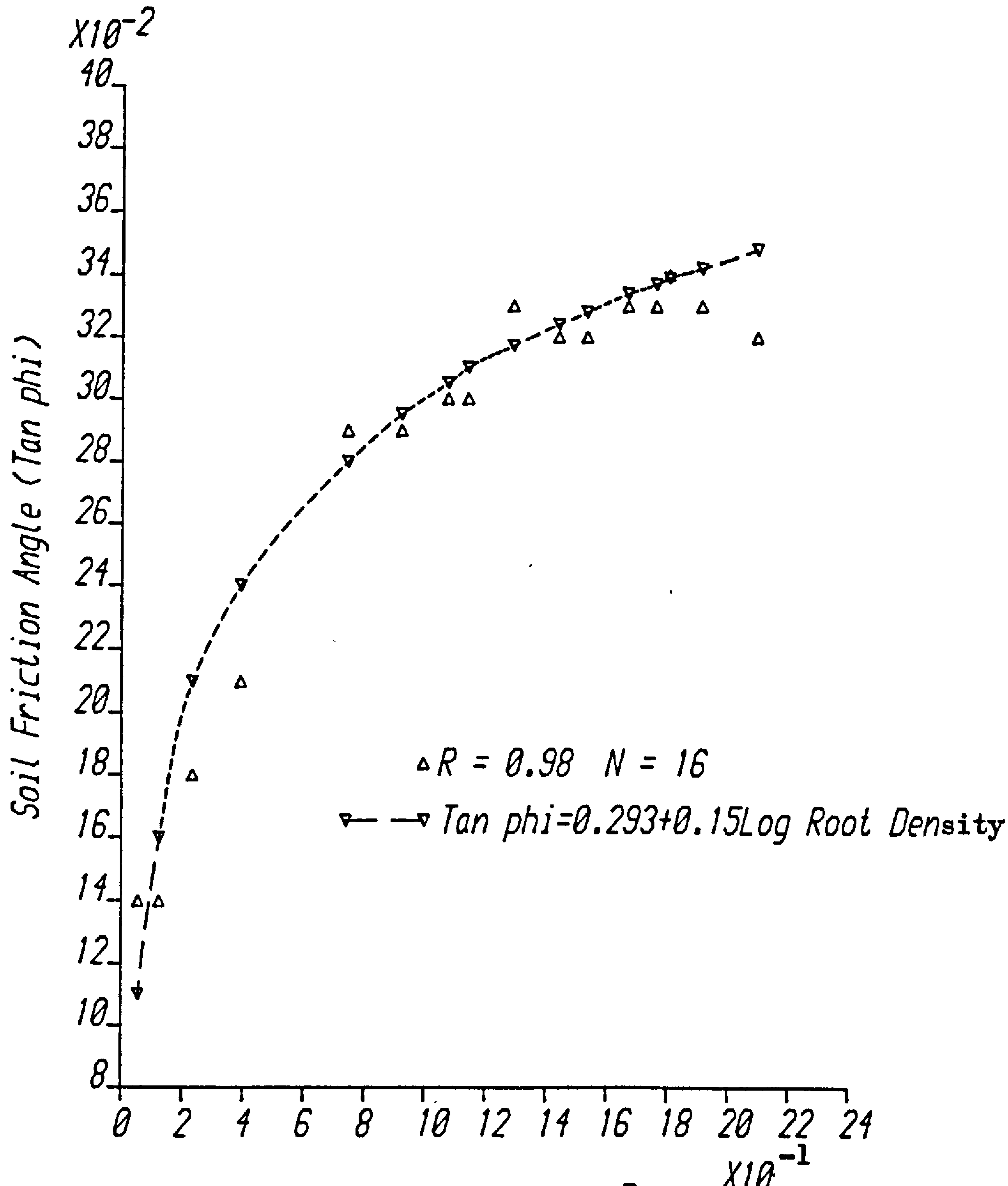


FIGURE 5.3 THE RELATIONSHIP BETWEEN ROOT DENSITY AND SOIL FRICTION (SANDY CLAY LOAM)

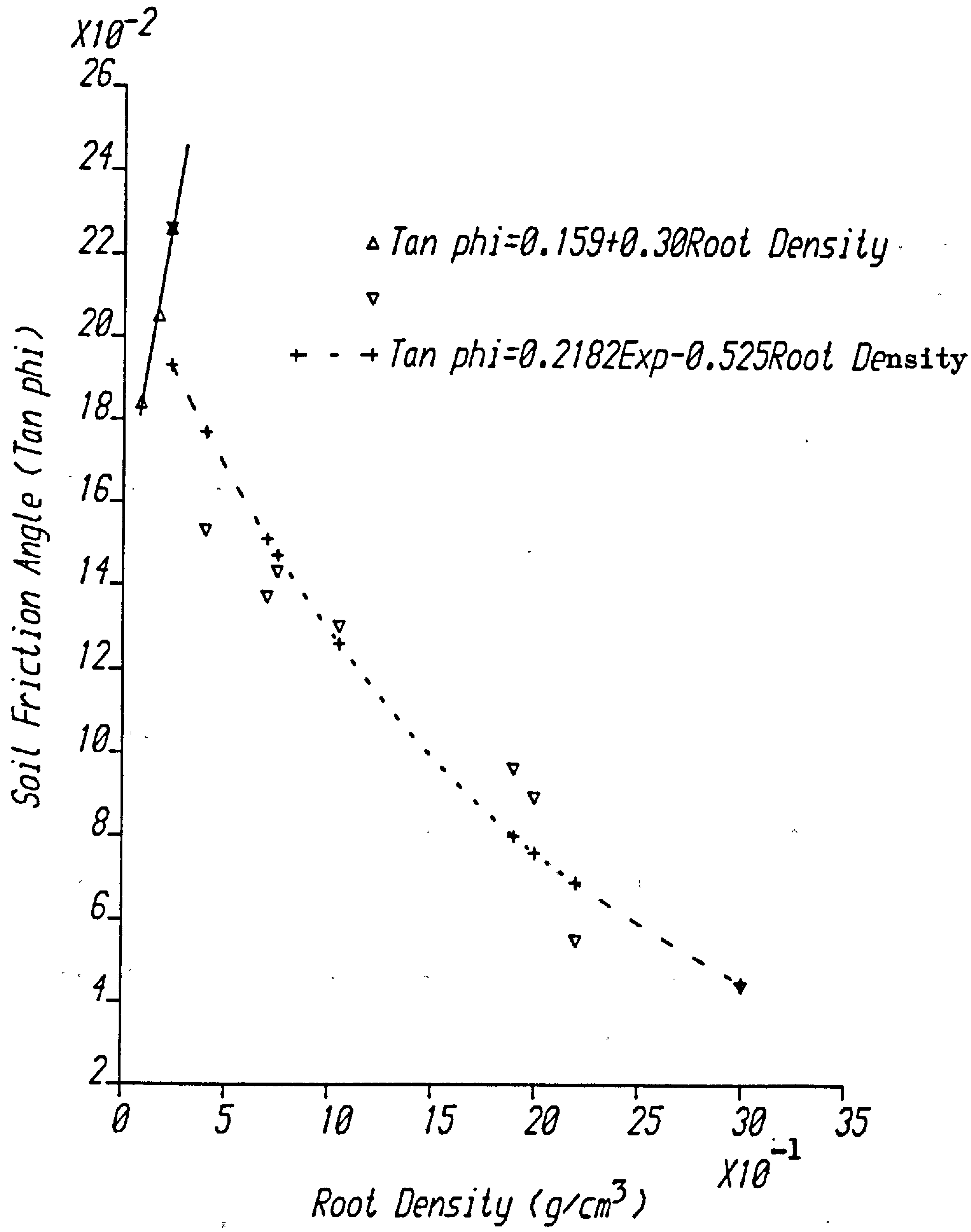


FIGURE 5.4 THE RELATIONSHIP BETWEEN ROOT DENSITY AND SOIL FRICTION (CLAY SOIL)

gravel soil which has particle size distribution characteristics that are different from those of the soils used in this study (Table 3.1). This difference in soil characteristics, and the difference in the shear strength measuring devices used in both studies (Ohu et al, 1986) may explain the marked difference in the magnitude of the cohesion values observed. Endo and Tsuruta's lower root-free cohesion value of 35 kg/m^2 (0.35 kPa) was obtained for soils that are different from those used in this study and with moisture characteristics that are not known from the English summary of the Japanese text. Their results cannot therefore be directly compared with those obtained in this study.

The graphs in Figures 5.1 and 5.2 show that, in the root-permeated soils, cohesion increases with root density. In both soils the pattern of increase is similar. At low root densities, cohesion increases rapidly with increasing root density; but as the root densities continue to increase beyond about 500 kg/m^3 (0.5g/cm^3) in the clay, and 700 kg/m^3 (0.7g/cm^3) in the sandy clay loam, additional increases in cohesion become smaller. These results may mean that, at saturation moisture content, the shear strength of root-free soils can be greatly increased through cohesion provided by the presence of roots but that when these soils become permeated with 0.5 g/cm^3 and 0.7 g/cm^3 of roots, subsequent increases in root density may only minimally increase the shear strength of the soils.

The cohesion - root density relationships observed in both soils are best described by the general regression equation relating cohesion to the common logarithm of root density (g/cm^3). In the sandy clay loam, cohesion increases by about 8.6 kPa for a unit increase in the log of the root density (Fig. 5.1); in the clay soil, the rate of increase is higher at about 10 kPa (Figure 5.2). The high correlation coefficients of 0.988 (sandy clay loam) and 0.99 (clay soil), both significant at better than the 95% confidence level, indicate the existence of a strong logarithmic association between the cohesion of the soils and their root densities.

It is generally accepted that roots in soils increase cohesion. However, the pattern of this increase with root density is not known. These results not only, therefore, confirm that roots in soils increase their cohesive strength, but more importantly, provide evidence to show that cohesion increases as the logarithm of the root density. As was indicated in Chapter 4.3.2 on the discussion of the effects of roots on shear strength increase with soil drying, adhesion also contributes to the observed cohesion increases with root density. However, since adhesion cannot yet be easily measured, its effect is assumed to be accounted for by the cohesion effect. Since the cohesion - root density relationship has only been determined for soils at saturation, further research is needed to verify this relationship at drier soil moisture contents.

5.3.2 The Effect of Root Density on Soil Friction

In discussions on the effect of roots on the shear strength of soils (Endo and Tsuruta, 1968; Gray and Leiser, 1982; Waldron 1977; Wu et al, 1979), it is generally accepted that their effect is mainly to increase cohesion with little or no effect on friction. Experiments by Kassiff and Kopelovitz (1968) using artificial fibres indicate that this is the case; they found that soil friction did not alter considerably with changes in fibre density. They however acknowledge that using artificial fibres instead of actual roots was a limitation in their study and so suggested that tests be carried out in experiments with actual roots. This section therefore discusses results of experiments with soils permeated with live roots to test the effect of varying root densities on the frictional strengths of the two soils used in this study. The soil friction - root density data in Appendix 5.1 shows that the angle of internal friction for root-free soils is 30^{o} for the sandy clay loam and 6.67^{o} for the clay. The data also show that in the root-permeated soils, all increases in root density were accompanied by changes in the frictional characteristics of the soils. Friction in the sandy clay loam consistently increased with root density whilst in the clay, it increased at first, and then decreased. In the sandy clay loam, soil friction angle increases from the root-free 30^{o} to 41.99^{o} at about 2.1 g/cm^3 root density. In the clay, friction increases from the root-free 6.67^{o} to 18.93^{o} at 0.23 g/cm^3 root density; subsequent increases in root density show a decrease in friction down to about 9.15^{o} at root density of 3.0 g/cm^3. It should be noted that although friction decreased at the higher root densities, the lowest friction value obtained at the root-density of $3g/cm^3$ is still higher than the root-free friction of 6.67^{o}.

The soil friction change - root density relationships for both soils are shown in Figures 5.3 and 5.4. The relationship shown in Figure 5.3 is best described by a logarithmic regression equation. This implies that soil friction increases with the logarithm of the root density. In the sandy clay loam, friction increases at an average rate of 8.53^{o} for a unit increase in the logarithm of root density. The high correlation coefficient ($r = 0.98$), significant at better than the 95% confidence level, indicates the existence of a strong friction - root density relationship. The coefficient of determination indicates that about 95% of the observed changes in the frictional characteristics of the soils is associated with the observed increases in root density. These results can be explained by the fact that the sandy clay loam soils have a very high percentage of sand (77%) so that the interlocking of a large number of sand-sized particles in the root-free soils leads to a high soil friction value observed for the root-free soil. In root-permeated samples, the root reinforcement and adhesion effects would bring these sand particles closer together and so increase the frictional resistance of the soils. These, and the results in section 5.3.1 show that the presence of roots increases both the cohesional and frictional characteristics of the sandy clay loam soils investigated.

Figure 5.4 shows the friction change - root density relationships observed in the clay soil. As root densities increase up to 0.23 g/cm^3, soil friction linearly increases; the rate of increase of friction within this root density range is very small at 0.005^o for a unit increase in root density. The correlation coefficient of this relationship is high ($r = 0.995$), implying a likely increase in friction with root density. However, the correlation coefficient is not significant at the 95% confidence level. This implies that a significant relationship between an increase in soil friction with root density cannot be said to have been established. This is undoubtedly due to the fact that very few parameter values ($N = 3$) were used in deriving the correlation coefficient of this relationship, rather than to the non-existence of a relationship. It should therefore be instructive to investigate this relationship using a large number of root density values within this low root density range.

Nevertheless, the low observed increases in friction can be explained by the fact that the clay soils have a very low proportion of sand particles (19%) which contribute to the frictional increases in the soils. Because of this, root-free friction in these soils is proportionately lower than was observed in the sandy clay loam soil. However, when the roots reinforce and bind the soil particles thereby bringing them closer together, increases in the interparticle friction among the small proportion of sand particles would increase the frictional strength of the soil, even if only minimally.

The other relationship shown in Figure 5.4 is that, as root densities increase from $0.4 g/cm^3$, soil friction changes decrease exponentially from 10.92^o to 2.6^o. This relationship is best described by the regression equation shown (Fig. 5.4). The correlation coefficient of this relationship is high ($r = -0.96$) and significant at better than the 95% confidence level. This implies that a statistically strong association can be expected to exist between decreasing friction with increasing root density. The high coefficient of determination indicates that about 92% of the observed decrease in friction can be explained in terms of increases in root density. As explained in the previous paragraph, root density increases up to about $0.23 g/cm^3$ may be expected to increase friction in these soils. It seems, however, that as root densities increase from about $0.4 g/cm^3$ to $3.0 g/cm^3$, the interparticle distances among an increasing proportion of the low percentage of sand particles, are increased. This can lead to a decrease in the sand grain-to-sand grain friction and hence to a decrease in soil friction. The rate of decrease, however, is very small at only 0.01^o for a unit increase in root density.

The results in this section have indicated that increases in root density affect the frictional characteristics of the sandy clay loam and clay soils very differently. Whilst in the clay the effect is to both increase and then decrease friction by very small amounts, in the sandy clay loam, the effect is to increase significantly frictional strength throughout the range of root densities investigated. It is suggested that this observed difference in the effect of roots on soil friction may be related to the proportion of sand-sized particles in the soils. Further research is however needed to verify this more fully and to determine the minimum soil sandiness below which root density may not increase soil friction at this moisture content. Research is also needed to determine the nature of root density effects on soil friction at other soil moisture contents.

5.4 Summary of Findings

The main finding in this Chapter is that increases in root density affect not only the cohesive strength of soils, as is generally thought, but also the angle of internal friction. In the sandy clay loam, the effect is to increase both shear strength parameters at almost equal rates for unit increases in root density. In the clay soil, it is found that small increases in root density, up to 0.23 g/cm^3, can increase both cohesion and friction; cohesion increases faster at the rate of about 10 kPa for a unit increase in root density whilst friction is increased by only a small fraction of a degree (0.005°) for a unit increase in root density. At higher root densities of 0.4 g/cm^3 and above, it is found that cohesion continues to increase but that soil friction decreases exponentially, again as in the increase, by only a small fraction of a degree (0.01°) for a unit increase in root density.

CHAPTER SIX

THE EFFECTS OF VEGETATION PARAMETERS ON BANK SCOUR

6.1 Background

This chapter is concerned with the effects of root and shoot densities of grass vegetation on the hydraulics of flow and on the scour resistance of channel banks. The flow hydraulics discussed include the Froude and Reynold's numbers, and Manning's retardance coefficient, n. Scour resistance is evaluated in terms of the tractive forces, up to the critical tractive forces, of the flowing water acting on the channel materials. The critical tractive force is defined as the tractive force of the flowing water which a channel material can sustain without causing excessive scour. This condition is considered to have occurred in the experiments when flows become cloudy and then muddy as a result of soil dispersal and when noticeable soil surface degradation begins. In this study, this condition is regarded as the maximum tractive/scour resistance of the sample, and is analogous to the permissible tractive force (Smerdon and Beasley, 1961).

In determining the effects of the vegetation roots on flow characteristics and scour, Froude and Reynold's numbers, Manning's n and CTF were determined for flume flows on 10 bare sandy clay loam soils permeated with live root densities ranging from 0 g/cm^3 to 1.8 g/cm^3, and on 4 bare clay soils with root densities from 0 g/cm^3 to 0.6 g/cm^3. Each of these samples is subjected to a controlled 40-minute sequence of gradually increasing flows of clear flowing water, beginning with a very thin flow of about 3 mm, until incipient scour is observed to have occurred at CTF flows. All flows were at a constant 2^o flume channel bed slope and for each average flow depth there was a unique average flow velocity (see Chapter 3.2 and 3.5.1). The Froude and Reynold's numbers, Manning's n and CTF values calculated for the velocity and depth measurements made for each flow on each sample (Chapter 3.5.1) are presented in Appendix 6.1. For each soil, the variation of each of these parameter values with flow for the root-free soil is compared with the variations observed for the increasing root density samples in order to determine the effect of roots.

In order to assess the effects of the vegetation shoots, the Froude and Reynold's numbers, Manning's n and tractive force values were also similarly determined for five vegetation densities; 80, 100, 150, 180 and 200 stands/m^2. These data are presented in Appendix 6.2. It should be pointed out that the grass vegetation used, Lolium perenne (Loretta), produces multiple stems per stand. In the stand densities used in this study, each stand had an average of 10 stems. Also, the vegetated samples used were at the same growth stage, seeded at the same density, but with the stands thinned out to the required stand density. This was done in order to minimise the between-sample differences that were observed to occur in the structure of the plants growing in samples that were at the same growth stage but at different seeding densities. Only one growth stage (20 weeks) was used for all the samples mainly because it was thought that only then would the root density effects be similar in all samples. The heights of the plants in the samples average about 30 cm and ranged from 15 cm to 45 cm. The flow depths produced range from 0.013 m to 0.088 m in the grass vegetation, and 0.003 m to 0.033 m on the bare samples. The vegetated samples were subjected to the same in-coming discharges so that the relative effects of the vegetation densities on the measured hydraulic parameters could be assessed.

6.2 Discussion of Results

6.2.1 The Effects of Root Density on Channel Flow Hydraulics

6.2.1.1 The Effect of Root Density on Flow Regime: The Froude numbers (F) of flows on all bare (root-free and root-permeated) soil samples are greater than unity (Appendix 6.1). On each sample, the magnitude of the Froude numbers generally increases with discharge. These results mean that the flows on bare soils are all in the supercritical state and become increasingly so with increases in flow velocity. This is because the roughness produced on bare soil surfaces mainly retards the initial low flows in contact with the soil surfaces; further increases in flow are therefore not retarded by the soil surface roughness elements.

The Reynolds' numbers (Re) for all the bare clay samples (Appendix 6.1B) are greater than 2,500; they range from about 4,000 at the low flows to a maximum of about 36,000 for the highest flow depth at which incipient scour was observed on the sample with the highest root density of 0.6 g/cm^3. The variation of Re values with flow depth up to the depths at which incipient scour was observed for all the clay samples is represented in Figure 6.1. This shows that Re values increase linearly with flow depth on all samples and that, for comparable flow depths, Re values are not very different for bare clay soils with different root densities. Maximum Re values vary between samples because higher discharges, which possess higher Re values, are required to scour the samples with the higher root densities.

These patterns of variations of Re values with flow, and between root density samples, are also found to occur on the bare sandy clay loam soils (Figure 6.2.) However, reference to the data in Appendix 6.1A shows that the root-free Re of 1,900 for the sandy clay loam soils is lower than the Re values of 4,00 - 10,000 for the root-free clay soil. The data also show that root-permeated sandy clay loam soils, with similar root densities to the clay soils, have much lower magnitudes of Re at similar flows. For instance, for samples with root densities of about 0.6 g/cm^3 and for similar flows, the maximum Re value for the sandy clay loam sample is 16,000 and for the clay, is Re - 20,000.

Accepting that, for open channel flows, the transitional range from laminar to turbulent flows corresponds to Reynolds numbers of 500 to 2,000 (Chow, 1959), the range of Re values observed means that the supercritical flows on all the bare sandy clay loam and clay soils can be regarded as turbulent. It also shows that on root-permeated bare soil surfaces, flows generated more turbulence on clay than on sandy clay loam soils with similar root densities. The pattern of changes in Re values with flow on both soils indicates that turbulence on bare soils increased with discharge. However plots of Re values for flows on different root density samples (Figure 6.1

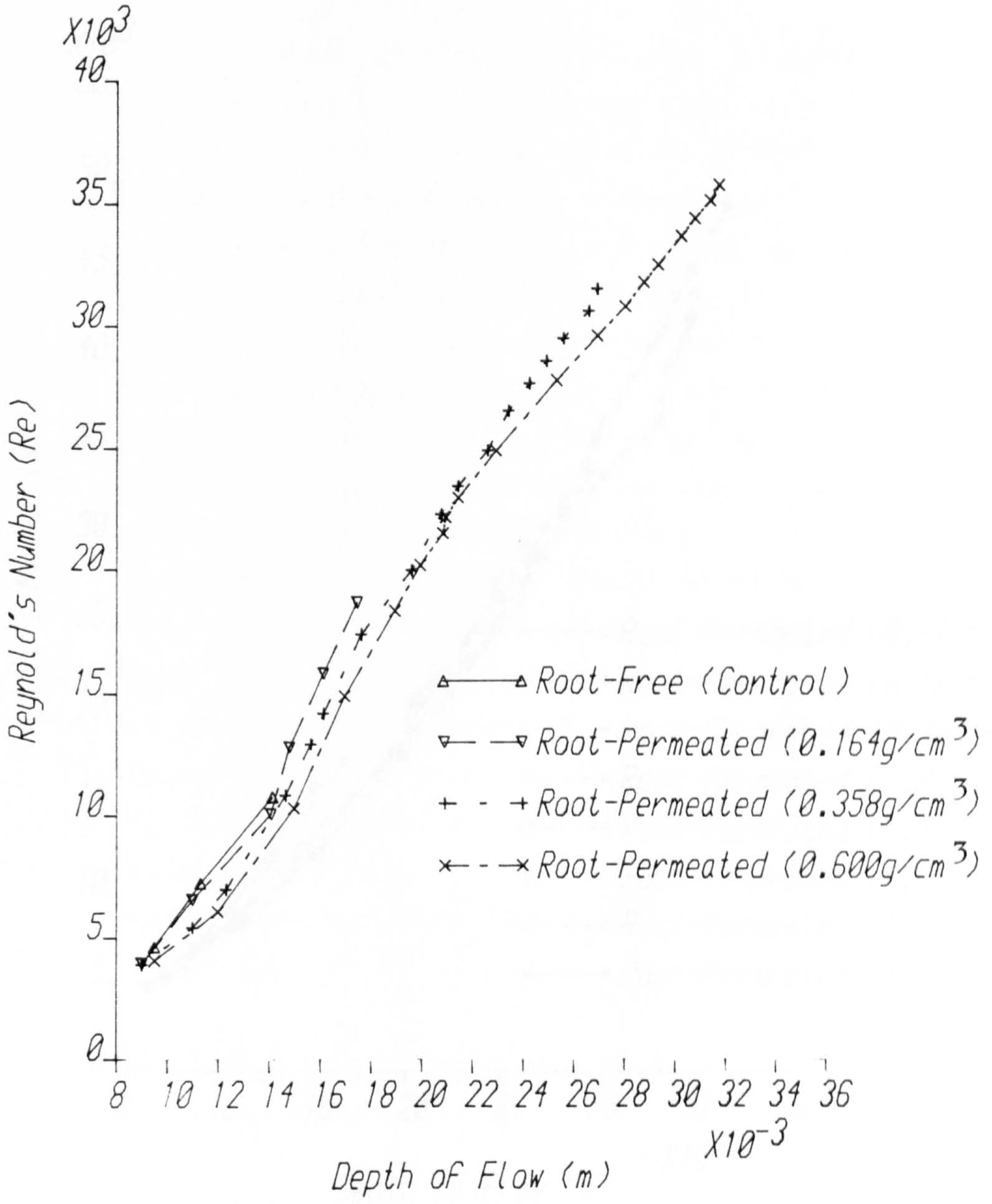


FIGURE 6.1 VARIATION OF REYNOLD'S NUMBER WITH DEPTH OF FLOW (BARE CLAY) (- CONSTANT BED SLOPE 2°)

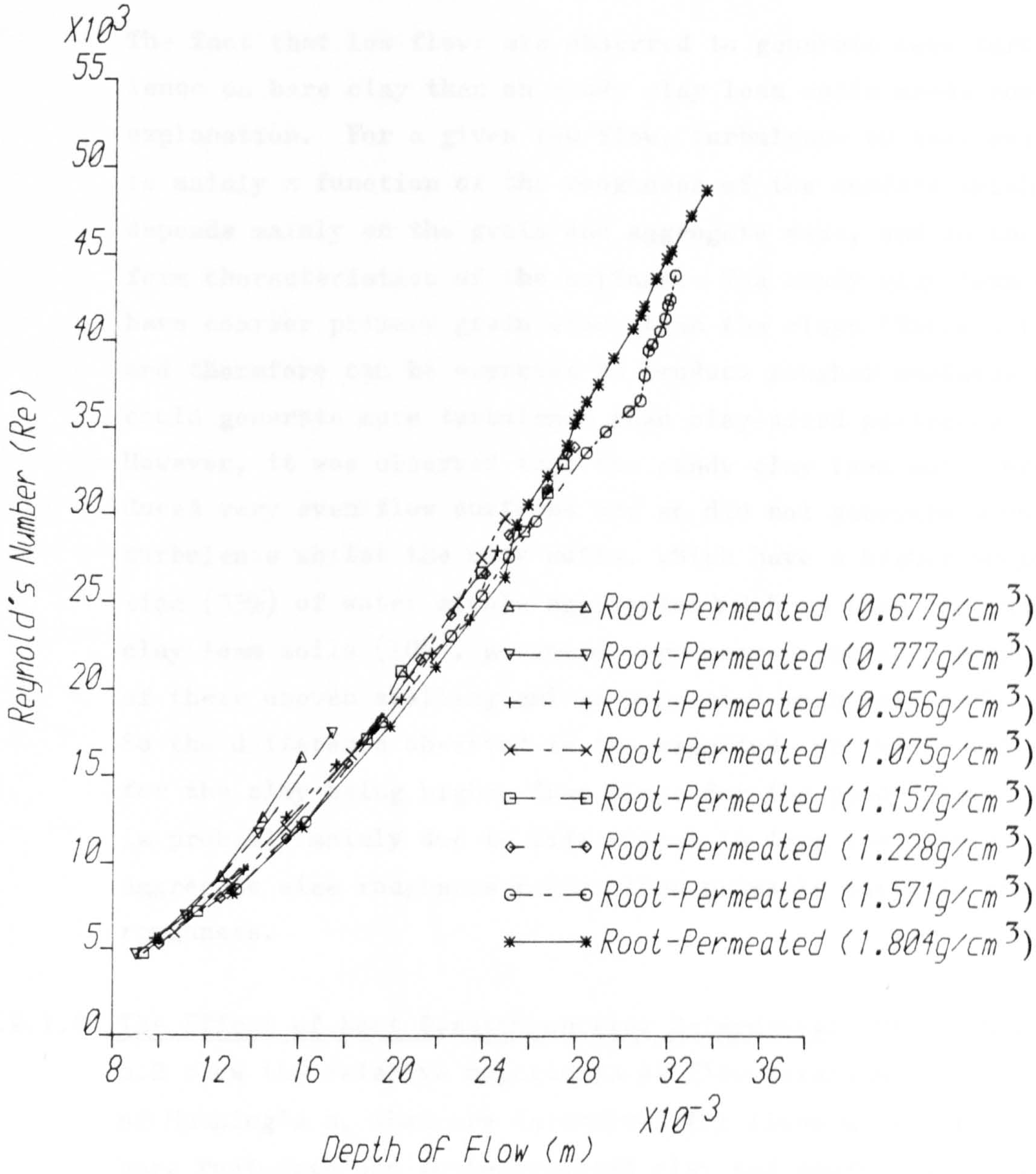


FIGURE 6.2 VARIATION OF REYNOLD'S NUMBER WITH DEPTH OF FLOW (BARE SANDY CLAY LOAM) (- CONSTANT BED SLOPE 2°)

and 6.2) show that, for comparable flow depths, Re - flow depth relationships may not be related to the root density variations among the samples. This is probably because roots do not alter the above-soil roughness characteristics which largely influence increases in turbulence with discharge (Chow, 1959).

The fact that low flows are observed to generate more turbulence on bare clay than on sandy clay loam soils needs some explanation. For a given low flow, turbulence on bare soils is mainly a function of the roughness of the surface which depends mainly on the grain and aggregate size, and on the form characteristics of the surface. The sandy clay loam soils have coarser primary grain sizes than the clays (Table 3.1) and therefore can be expected to produce rougher surfaces which could generate more turbulence than clay-sized particles. However, it was observed that the sandy clay loam soils produced very even flow surfaces and so did not generate much turbulence whilst the clay soils, which have a higher proportion (35%) of water stable aggregates $>$ 0.5 mm than the sandy clay loam soils (10%), produced very uneven surfaces because of their uneven swelling and so generated much more turbulence. So the difference observed in the magnitude of the Re values for the clay being higher than those for the sandy clay loam is probably mainly due to differences in form and stable aggregate size roughness rather than primarly particle size roughness.

6.2.1.2 <u>The Effect of Root Density on Flow Retardance</u>: Tables 6.1 and 6.2 show the relative magnitudes of flow retardance, in terms of Manning's n, that are determined for flows up to CTF on bare root-free and root-permeated clay and sandy clay loam soils respectively. It should be emphasised that the object of this section is to determine the relative effects of root-permeated soils, as compared to root-free soils, on flow retardance in terms of Manning's n, at a constant channel bed slope (2^o). The absolute n values determined are therefore not definitive but relate only to the experimental conditions. For instance if the same flows used in these experiments are generated in channels with larger or smaller cross-sectional areas, or with bed slopes that are steeper or gentler than 2^o,

TABLE 6.1: MANNING'S n VALUES FOR THE CLAY SOIL (2^o BED SLOPE)

Root Density g/cm^3	Manning's n_s and n_{rs}	% increase of n relative to root-free
Root-free (control)	n_s = 0.017 - 0.014	-
0.164	n_{rs} = 0.018 - 0.012	6
0.358	= 0.018 - 0.013	6
0.600	= 0.019 - 0.013	12

TABLE 6.2: MANNING'S n VALUES FOR THE SANDY CLAY LOAM SOIL(2^o BED SLOPE)

Root Density g/cm^3	Manning's n_s and n_{rs}	% increase of n relative to root-free
Root-free (Control)	n_s = 0.008	-
0.100	n_{rs} = 0.014 - 0.012	75
0.677	= 0.015 - 0.012	88
0.777	= 0.015 - 0.012	88
0.956	= 0.015 - 0.014	88
1.075	= 0.016 - 0.013	100
1.157	= 0.016 - 0.013	100
1.228	= 0.016 - 0.014	100
1.571	= 0.016 - 0.014	100
1.804	= 0.016 - 0.013	100

the absolute magnitudes of the n values may be different although the relative differences would still be observed (Chow, 1959; Einstein and Barbarrosa, 1952; Lane, 1955).

These data show that Manning's retardance coefficient values for the clays are relatively greater than the values for the sandy clay loam. Manning's n for the root-free clay, for instance, ranges from $n_s = 0.014$ to 0.017 whilst for the sandy clay loam, it is much lower at $n_s = 0.008$; the maximum clay retardance coefficient for root-free soil of $n_s = 0.017$ is even higher than the maximum n_{rs} of 0.016 obtained for the sandy clay loam with the highest root density of about 1.8 g/cm^3. As observed in the previous section (6.2.1.1), this difference in the magnitudes of the flow retardance of the two soils can be explained in terms of differences in form roughness.

Another important feature of the data in these tables is that, for both soils, higher Manning's n values were obtained for samples with higher root densities. The observed magnitudes of Manning's n were certainly not contributed to by leaves and other decaying vegetal matter which normally accumulated on the soil surfaces during vegetal growth because these were removed before the flow experiments were commenced. The observed increases in Manning's n with increases in root density are therefore interpreted to mean that increases in root density produce increases in soil surface roughness. For instance, the data in Table 6.1 show that for the clay soil, increases in Manning's n, relative to the root-free soil, range from 6% in soils with 0.164 g/cm^3 of roots, to 12% in soils with 0.6 g/cm^3 of roots. In the sandy clay loam soil (Table 6.2), the percentage increases are considerably greater in magnitude than in the clay; for instance, the sandy clay loam soil with 0.1 g/cm^3 of roots has a 75% increase in Manning's n relative to the root-free roughness coefficient value.

It is not clear, from this study, precisely how increases in root density contribute to increases in the values of Manning's n. For example, it is known that increases in root density and root growth activities can lead to increases in soil shear strength and in soil aggregate stability; also, it has been observed that the introduction of grass in Crop Rotation practices can improve the structure of soil (Hudson, 1986); it is not however clearly known whether it is these rooting effects which increase the inherent roughness characteristics of the soils and so give rise to the increases in n values observed in root-permeated soils relative to the root-free soils. However, observations of the soil surfaces of the root-permeated bare soils before the initial experimental flows showed that a matting of fine roots can be observed very close to the surface of the soils. The roots were so close to the surface that their upper parts became exposed after the 40 minutes duration of the initial flows. Since the flow was allowed to stabilise for about 10 - 15 minutes before measurements were made, it could be expected that the flowing water was in actual contact with the exposed roots during flow measurements, thereby resulting in the high Manning's n values observed. It is not known whether the roots grew so close to the soil surfaces because of the shallow 15 cm depth limitation imposed on the downward growth of the roots by the sample boxes. However, it is known that under favourable surface soil conditions, more than 75% of the roots of plants have been observed to occur within the top 2.5 cm depth of the soil surface (Russell, 1977). Such a high concentration of roots so close to the soil surface can produce the condition observed on the sample surfaces, whereby the upper parts of the roots become exposed and so are in actual contact with the flows.

It is also not clear why initial increases in root density produce considerably higher percentage increases in n values, relative to the root-free soil, in the sandy clay loam than in the clay. A possible reason is that, for the clay soil, which has high root-free roughness effects, the soil and initial root roughness effects are probably not addictive. So that as the roots develop initially, their roughness effect replaces rather than adds to the roughness effect of the soil. In the sandy clay loam soil, the roots probably give greater retardance than the primary sandy soil grains but similar retardance to the aggregates of the clay soil.

Another observation made on the samples is that mound-like bulges of the soil surfaces occurred around the points from which the vegetation shoots were cut. These bulges were more prominent on samples that were at higher growth stages and as such had produced more multiple stems per vegetation stand than on samples at shorter growth stages which had fewer multiple stems. Roots are known to grow very profusely under the stems of plants (Epstein, 1973; Marshall and Holmes, 1979; Russell, 1977). As these roots grow, they push the soil aggregates apart and locally increase the volume of the soil; this could cause the soil surface to bulge outwards with the bulge increasing with the density of the roots growing in the soil. In this way, increases in form roughness could be produced by root growth which could lead to high magnitudes of n values especially in the sandy clay loam soils.

A third feature of the data in Tables 6.1 and 6.2 is that, in both soils, values of Manning's n vary considerably within samples. Figure 6.3 shows that this variation, in the sandy clay loam soils, is related to the depth of flow on the soils. The graphs show that, in general, Manning's n decreases with increases in flow depth. It should be pointed out that the minimum n values of the graphs represent the flow retardance at the CTF (incipient scour) flow depths on each sample. An explanation of this pattern of Manning's n variation with flow depth is that, at the initial very low flow depths, the flow retardance effects are at their highest. This is because the flows encounter the maximum resistance produced by the surface roughness characteristics. As shown in the previous section (6.2.1.1), such flows are less

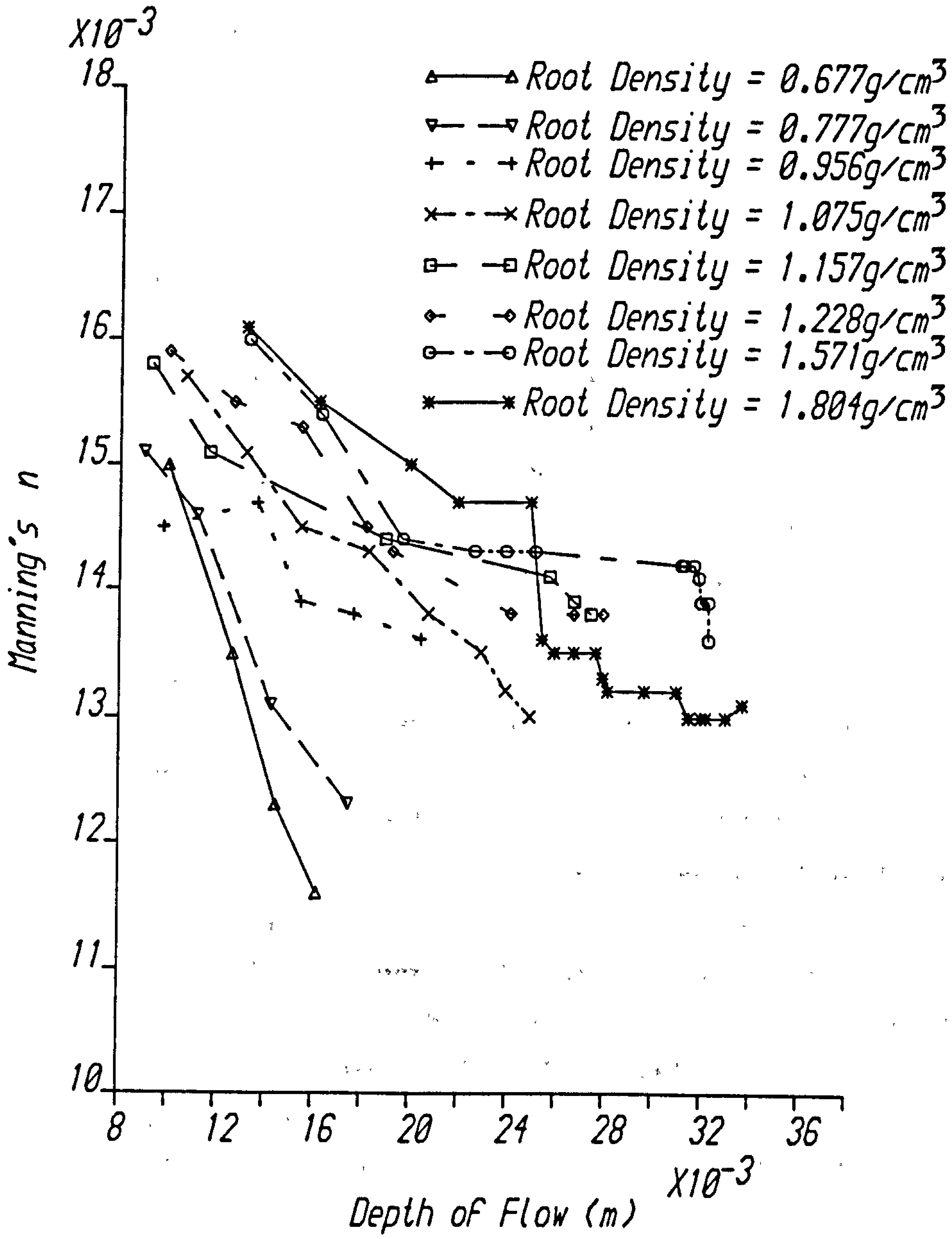


FIGURE 6.3 VARIATION OF CALCULATED MANNING'S n* WITH DEPTH OF FLOW AT CONSTANT 2^{o} BED SLOPE (BARE SANDY CLAY LOAM)

*calculated from Manning's Equation (2.3)

supercritical (lower F values) and less turbulent (lower Re values) and therefore less erosive than higher flows. As flow depths increase, they do not encounter any additional surface roughness resistance and so the value of the Manning's n decreases. The trends in the graphs show that, for the low root density samples, this decrease in Manning's n with increase in flow depth continues until CTF (incipient scour) flow depths. For the highest root density sample, local increases in Manning's n occurred at the higher/intermediate flows but these tended to level off as incipient scour was observed.

The pattern of Manning's n variation with flow depth for the clay soil is shown in Figure 6.4. This pattern of variation is similar to that observed for the sandy clay loam. The only difference is that for the clay samples with the highest root densities of 0.358 and 0.6 g/cm^3, the initial decrease in n with flow depth is followed by an apparent levelling off and then a consistent increase in n until incipient scour. Comparing this pattern of change in n with that observed for the sandy clay loam sample with a similar root density of 0.677 g/cm^3 (Figure 6.3), then the difference can be explained as follows: Figure 6.4 shows that for the clay, increases in n occur as flow depths increased from 0.022m; reference to Figure 6.1 shows that at that flow depth, the magnitude of turbulence, in terms of Reynold's numbers, was high at Re = 25,000. This implies that further increases in turbulence produced the observed increases in n. For the sandy clay loam sample, however, Figure 6.3 shows that it was already eroded at a lower flow depth of 0.016 m and Figure 6.2 shows that at that flow depth the degree of turbulence was much lower than for the clay, at about Re = 15,000. In any case, this pattern of increasing Manning's n with flow, at depths many times higher than the roughness components of the bare soils, is clearly different from the

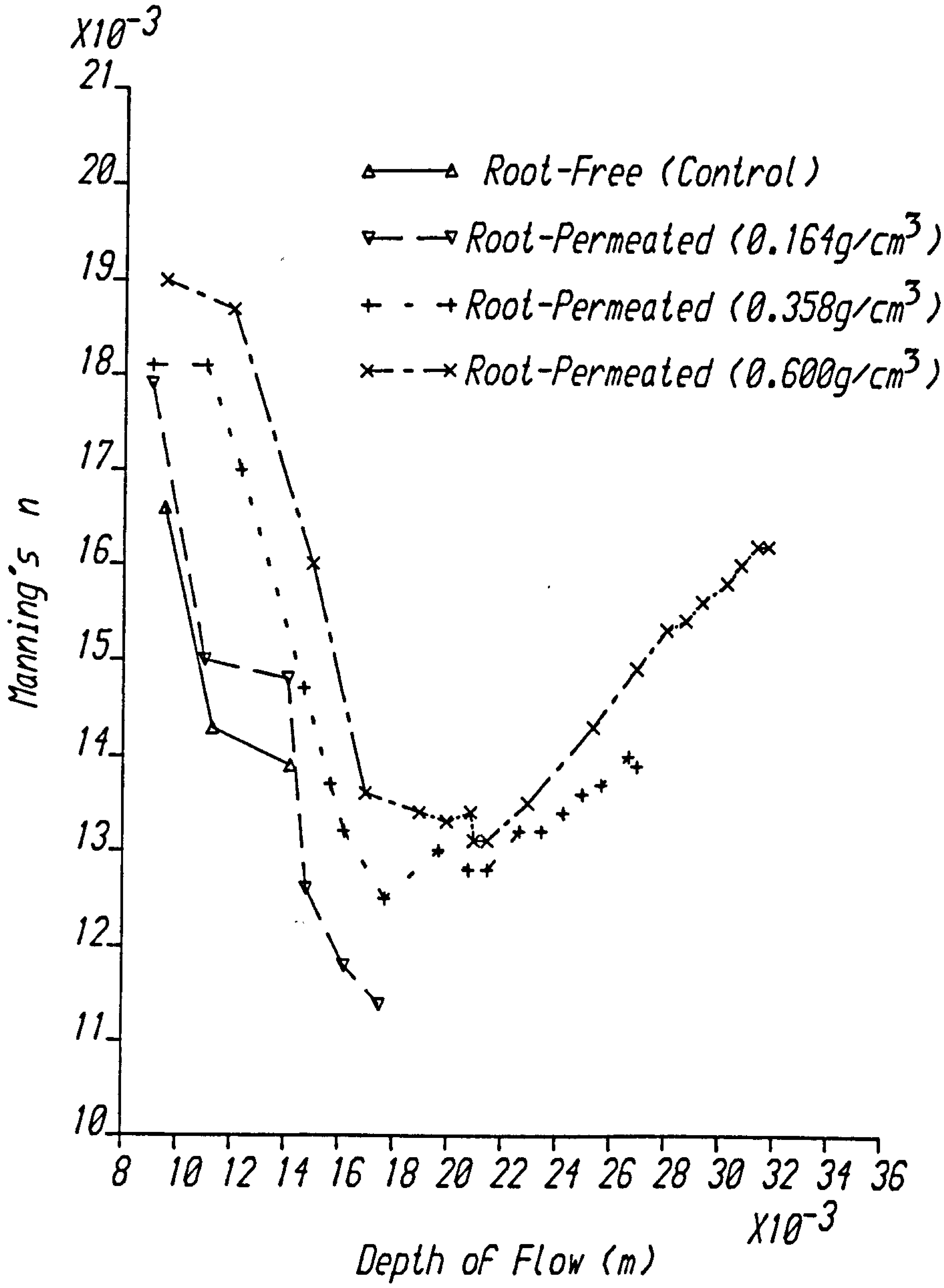


FIGURE 6.4 <u>VARIATION OF CALCULATED MANNING'S n* WITH DEPTH OF FLOW AT CONSTANT 2° BED SLOPE (BARE CLAY SOIL)</u>

*calculated from Manning's Equation (2.3)

constant n usually observed for vegetated channels in which flow depths are above the height of the vegetation (Cooke and Campbell, 1939; Ramser, 1943; Ree and Palmer, 1949). A possible explanation for this may be that on the bare soils, increases in flow depth generate increases in turbulence which lead to increases in n whilst in vegetated channels, when the flow flattens the vegetation to the bed of the channel, a smooth surface is produced on which increases in flow depth may not generate as much turbulence as observed on the bare soils and as a result, n values tend to become constant.

These results show that, in terms of Froude and Reynold's numbers, flows on bare (root-free and root-permeated) soils are very highly supercritical and turbulent and become increasingly so with increases in flow depth. The results also show that, for each soil, roots probably have no significant effect on the increases in Froude and Reynold's numbers which occur at comparable depths of flow. In terms of Manning's n, the results show that flow retardance decreases with increases in flow depth, with the magnitude of the root-free sandy clay loam soil retardance being less than half that of the clay soil. In each soil, retardance increases with increases in the root density of the soils, with the root density effect being greater in the sandy clay loam than in the clay soil. This last result is a particularly important finding because it highlights the importance of roots in retarding especially low flows and, consequently, the need for taking the effect of roots into account in reporting n values. This result also points out the need for further research into precisely how increases in root density contribute to increases in soil surface flow retardance and why roots apparently contribute more surface flow retardance to sandy clay loam than to clay soils.

6.2.2 The Effect of Vegetation Density on Channel Flow Hydraulics

6.2.2.1 The Effect of Vegetation Density on Flow Velocity and Depth:

The most important structural characteristic of a channel vegetation is its ability to protect the channel from scour by retarding the flowing water. In retarding flows, the vegetation decreases the velocity of the in-coming flow and consequently increases flow depth. The degree to which a given vegetation retards flow depends on its density characteristics.

Figure 6.5 shows the effect of vegetation density variations on in-coming flow velocities. As expected, the graphs show that the low density grass vegetation decreases flow velocities less, and so protects the channel material from scour less, than the high density vegetation. For instance, the two lowest densities of 80 and 100 stands/m^2 reduce the initial in-coming flow velocity of 0.67 m/s by 57 and 60% respectively, whilst the higher densities of 150, 180 and 200 stands/m^2 reduce this velocity by 73, 78 and 79% respectively. As the incoming flow velocities increase up to 1.05 m/s, the retarding effect of the vegetation decreases; this is reflected in the gently declining sections of the curves in Figure 6.5. The steeply declining sections of the curves representing the lower vegetation densities indicate that the resistance offered by these densities declines very rapidly when velocity increases beyond 1.05 m/s. At the maximum incoming flow velocity of 1.15 m/s, for instance, these densities retard only 18 and 19% of the velocity. This implies that at the high velocities, the low vegetation densities offer very little protection to the channel material against scour. It is of course not known at what percentage of reduction in velocity these vegetation densities would cease to protect from scour.

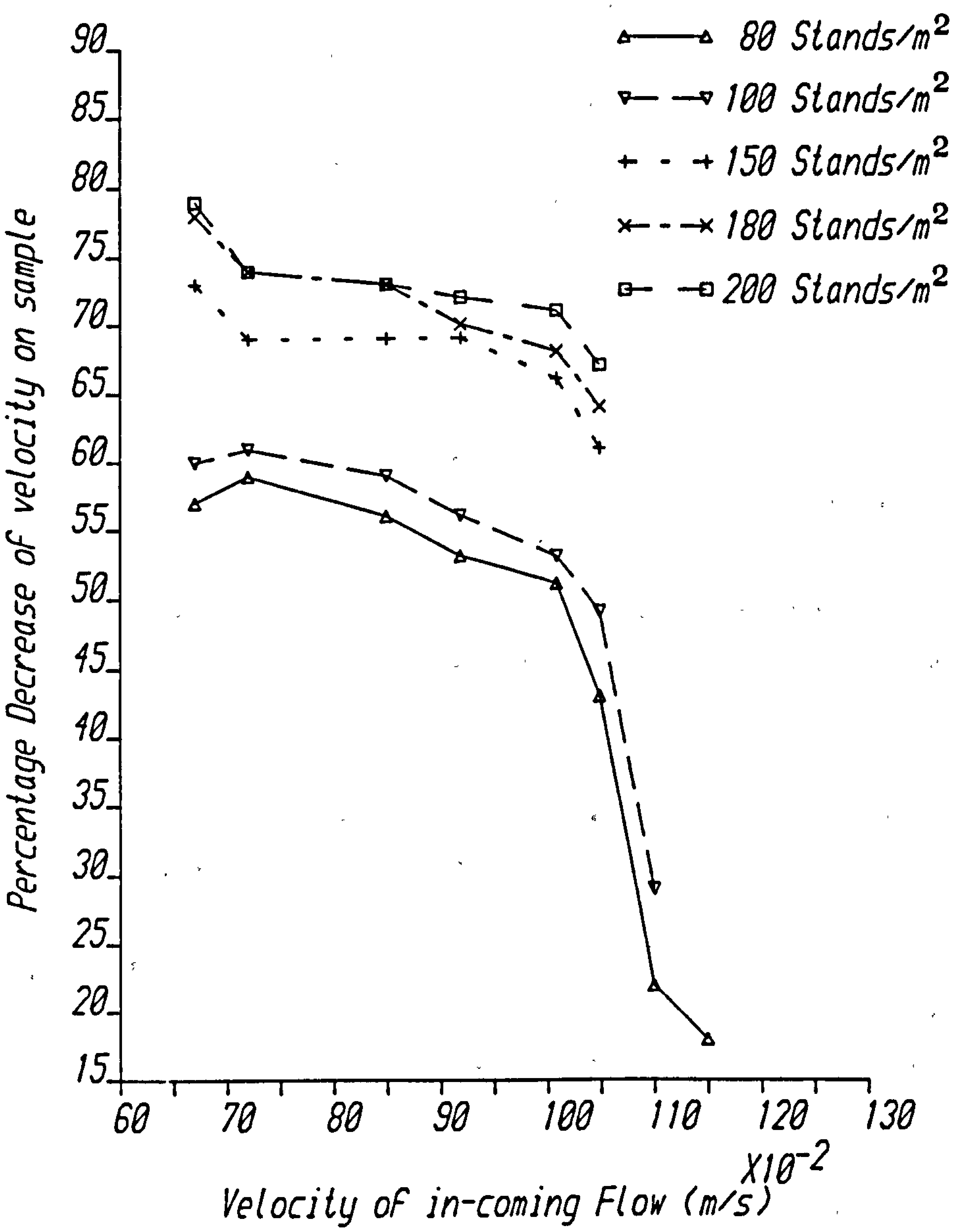


FIGURE 6.5 THE EFFECT OF VEGETATION DENSITY ON THE PERCENTAGE DECREASE OF FLOW VELOCITY - CONSTANT BED SLOPE 2^{o}

Comparative percentage velocity reductions could not be determined for the three higher vegetation densities for velocities greater than 1.05 m/s because of the limited capacity of the flume section.

Figure 6.6 shows the effect of vegetation density on incoming flow depths. Here also, as expected, the graphs show that for all incoming flows, low vegetation densities increase flow depths less than the high vegetation densities. At the initial incoming flow depth of 0.01m, the lowest vegetation density increased flow depth by only 30% whilst this percentage increased to 40, 58, 70 and 100% with increasing vegetation densities of 100, 150, 180 and 200 stands/m^2 respectively. As the incoming flow depths increase but remain below the height of the vegetation which was still erect, the percentage increase in flow depth in all vegetation densities continued to increase. At the incoming flow depth of 0.0295m, the curve of the lowest vegetation density shows a sharp decrease in the percentage increase in flow depth reflecting the stage at which only 18% of the flow velocity is retarded (Appendix 6.2); this also reflects the stage at which vegetation submergence, not complete flattening, was observed to occur.

6.2.2.2 <u>The Effect of Vegetation Density on Flow Regime</u>: An implication of reducing flow velocities and increasing flow depths is to produce flow regimes that are not erosive. Figure 6.7 shows the effect of vegetation density on the variation of Froude numbers with flow depth. The graphs show that at all flow depths, the higher the vegetation density, the lower the Froude number. For the two low vegetation densities (80 and 100 stands/m^2), all the Froude numbers are greater than unity but less than the minimum F determined for the bare soil surfaces. This means that flows in the low vegetation densities are supercritical but flow much less

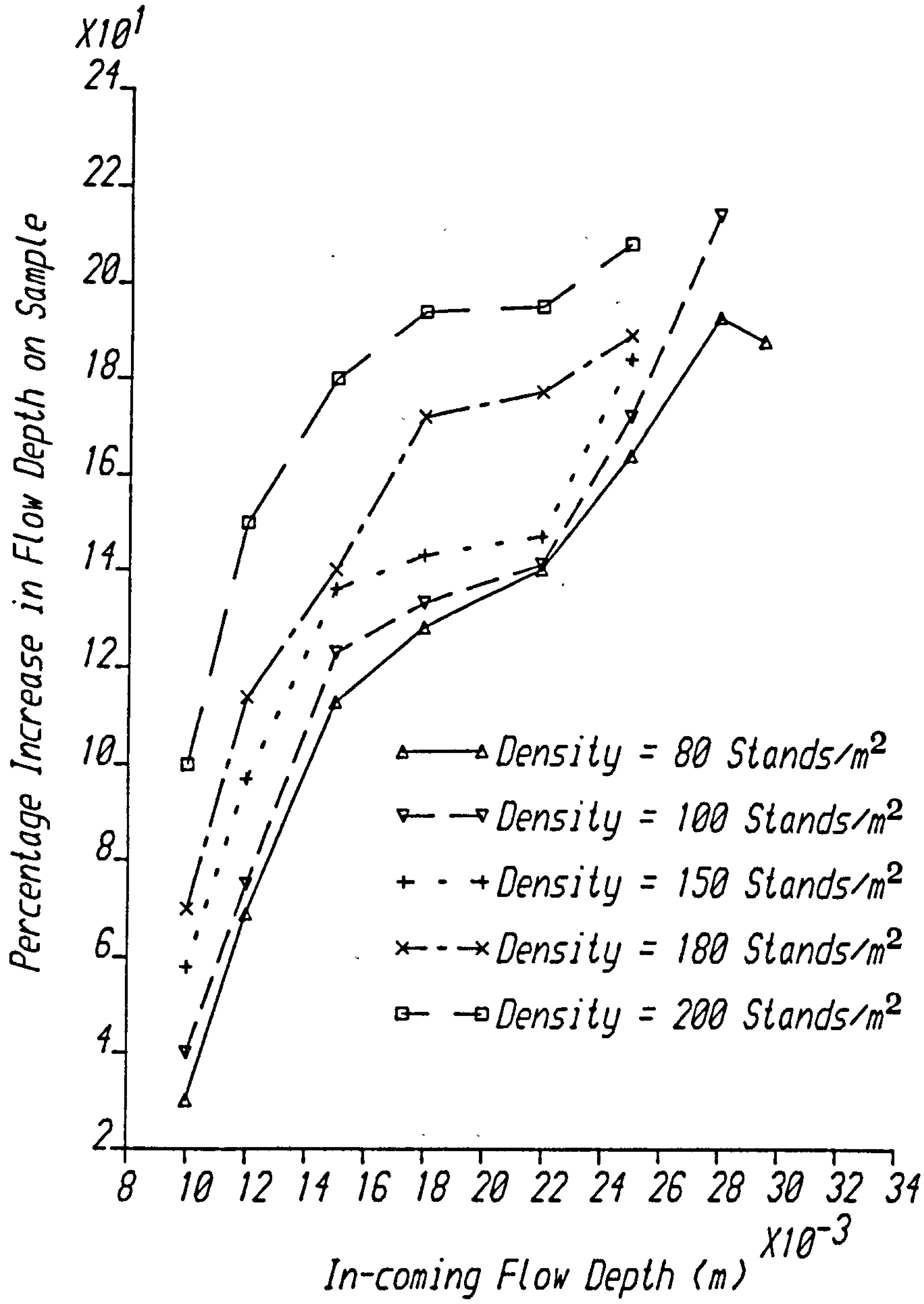


FIGURE 6.6 THE EFFECT OF VEGETATION DENSITY ON THE PERCENTAGE INCREASE OF FLOW DEPTH - CONSTANT BED SLOPE 2°

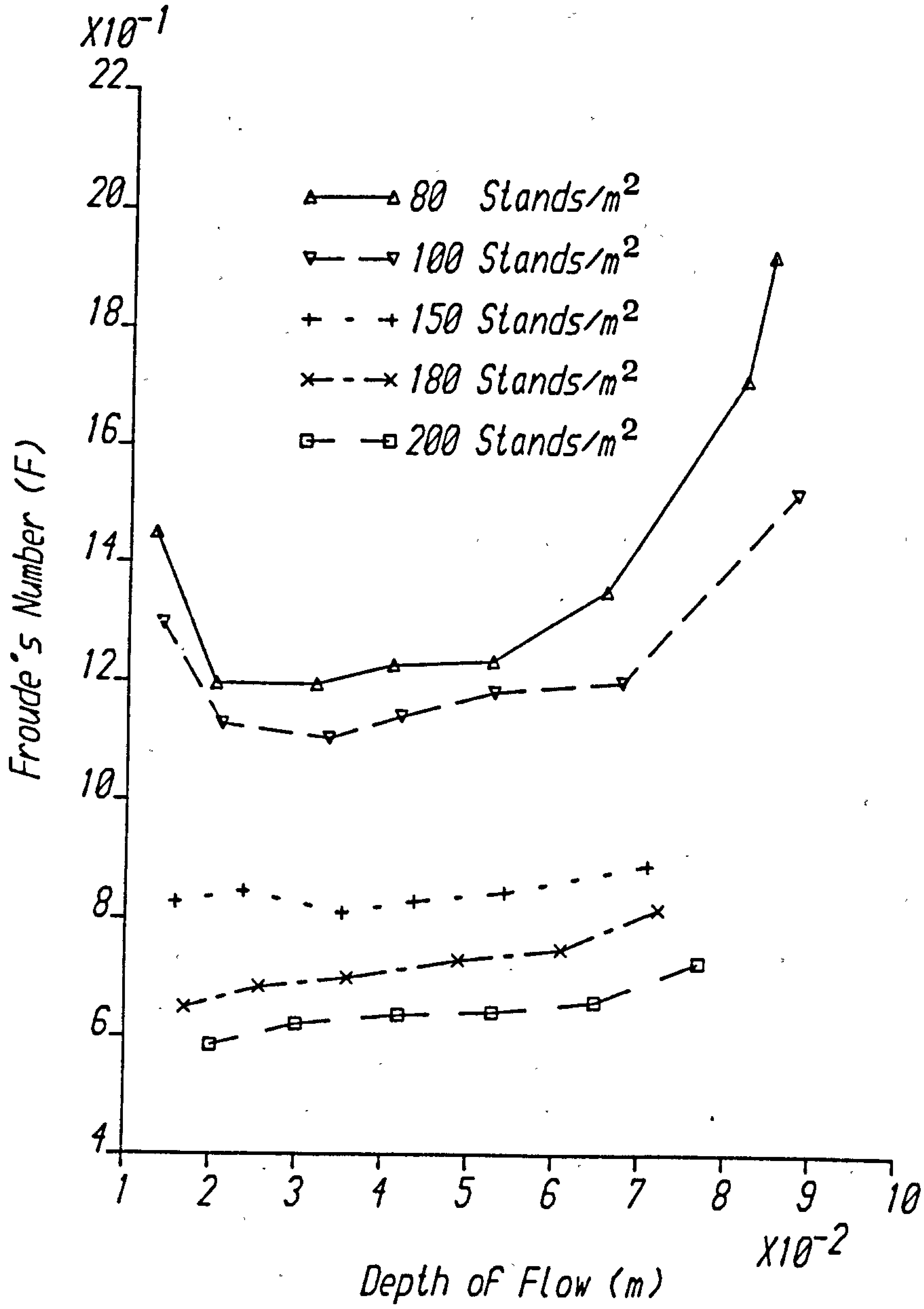


FIGURE 6.7 THE EFFECT OF VEGETATION DENSITY ON VARIATION OF FROUDE'S NUMBER WITH DEPTH OF FLOW - CONSTANT BED SLOPE 2^{o}

rapidly and so are less erosive than flows on bare soil surfaces. Froude numbers for flows in vegetation densities of 150 stands/m^2 and above are all less than unity. This means that the flows are all subcritical and so less erosive than flows in the lower vegetation densities.

It would appear from Figure 6.7, that the pattern of change of Froude numbers with flow depth in the supercritical flows of the lower vegetation densities is different from that in the subcritical flows of the higher vegetation densities. In the supercritical flows, Froude numbers first show a sharp decrease in magnitude before they start increasing as flow depth increases whereas in the subcritical flows, the Froude numbers increase with flow depth. A careful look at the graphs should reveal that this difference is due to the difference in the initial flow depths for which the Froude numbers were computed. As was seen in the previous section (Figure 6.6), high vegetation densities increase flow depths much more than low vegetation densities. The data in Appendix 6.2 show that the initial flow depths in the two low vegetation densities are 0.013 and 0.014m. At these depths, the flow encountered only the stems of the grass vegetation which offer relatively low resistance to flow as reflected in the initial high Froude numbers. As the flow depths increase, the flows encounter, in addition to the stems, a mass of foliage which increases flow retardance markedly, thereby producing flows that are less supercritical as is shown by the sharp decline of the curves to lower Froude numbers. With subsequent increases in flow depth within the foliage up to 0.08 m, the graphs show an increase in Froude numbers with flow depth as in the higher vegetation densities where the high initial flow depths, produced by their high flow retardance, were within the foliage of the vegetation. Above flow depths of 0.08m, the graphs of the low vegetation densities show a sharp increase in Froude numbers; this indicates a rapid increase in flow velocity as was also observed by the sharp decline in the percentage of incoming velocities reduced by the vegetation densities (See Figure 6.5). These results show that flows are more rapid in low than in high vegetation densities. Compared to bare soil surfaces, these results show that whereas flows on bare soils are all very highly supercritical (Section 6.2.2.1), flows in vegetation are less so, even at low vegetation densities, and become subcritical in high vegetation densities.

Figure 6.8 shows the variation of the Reynold's numbers of flows in varying vegetation densities. These curves show that Re values increase exponentially with flow depth and that at all flow depths, the magnitude of Re values increases with decreasing vegetation density. This means that turbulence increases with flow in each vegetation density and that flows in low vegetation densities are more turbulent than flows in high vegetation densities. As compared to bare root-permeated soils (Figures 6.1 and 6.2), the lower minimum Re values and the exponential increase in Reynold's number with flow depth observed in vegetation show that turbulence is lower and increases less rapidly with depth of flow than on bare soils.

6 2.2.3 The Effect of Vegetation Density on Flow Retardance:

Flow retardance in terms of Manning's n was determined for flows in five grass vegetation densities and results are presented in Table 6.3. The data show a range of n values for each vegetation density. This is because, as expected, flow retardance by a given vegetation varies with discharge. The data also show that the magnitude of n values is higher in high vegetation densities than in low vegetation densities. This is because, as seen in the previous section, high vegetation densities retard flow velocities much more than low vegetation densities.

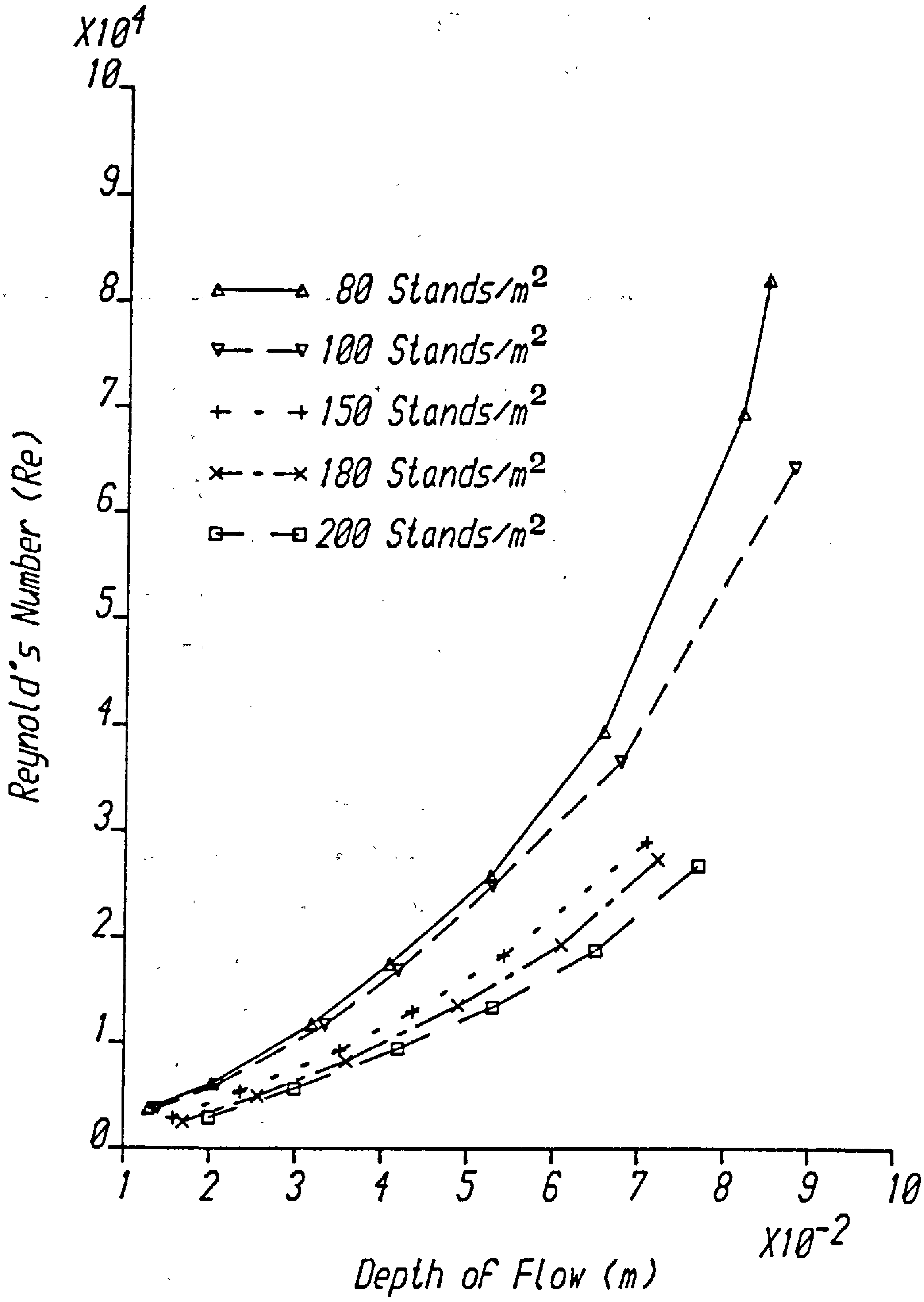


FIGURE 6.8 THE EFFECT OF VEGETATION DENSITY ON VARIATION OF REYNOLD'S NUMBER WITH DEPTH OF FLOW - CONSTANT SLOPE 2°

TABLE 6.3: MANNING'S n VALUES FOR GRASS VEGETATION (2^o BED SLOPE)

VEGETATION DENSITY (Stands/m^2)	MANNING'S n	ROOT DENSITY (g/cm^3)
80	0.035 - 0.052	
100	0.040 - 0.056	
150	0.064 - 0.077	1.80
180	0.082 - 0.088	
200	0.093 - 0.100	

The variations of Manning's n values with flow depth for the different vegetation densities are illustrated in Figure 6.9. The shapes of the curves for the different vegetation densities are generally similar. They show that n values increase with depth of flow up to a maximum value, and then decrease with further increases in flow depth.

This pattern of n variation with flow depth is as expected for low to intermediate flow magnitudes (Ree, 1949; Palmer, 1945). It is due to the fact that the initial shallow low velocity flows encounter resistance from only the bases of the stems of the grasses and from the soil surfaces; consequently the retardance coefficients are relatively low. As flow depth increases, an increasing bulk of the multiple stems and the foliage of the grasses is encountered; this leads to an increase in flow retardance which is reflected in the increase in the magnitude of n values. As flow depth increases further, a depth is reached when the flow resistance of the grass vegetation starts declining; this was reflected in the grass bending over and being submerged. This stage is represented by the decrease in the Manning's n curves. It was at this stage that the flow capacity of the flume was reached and

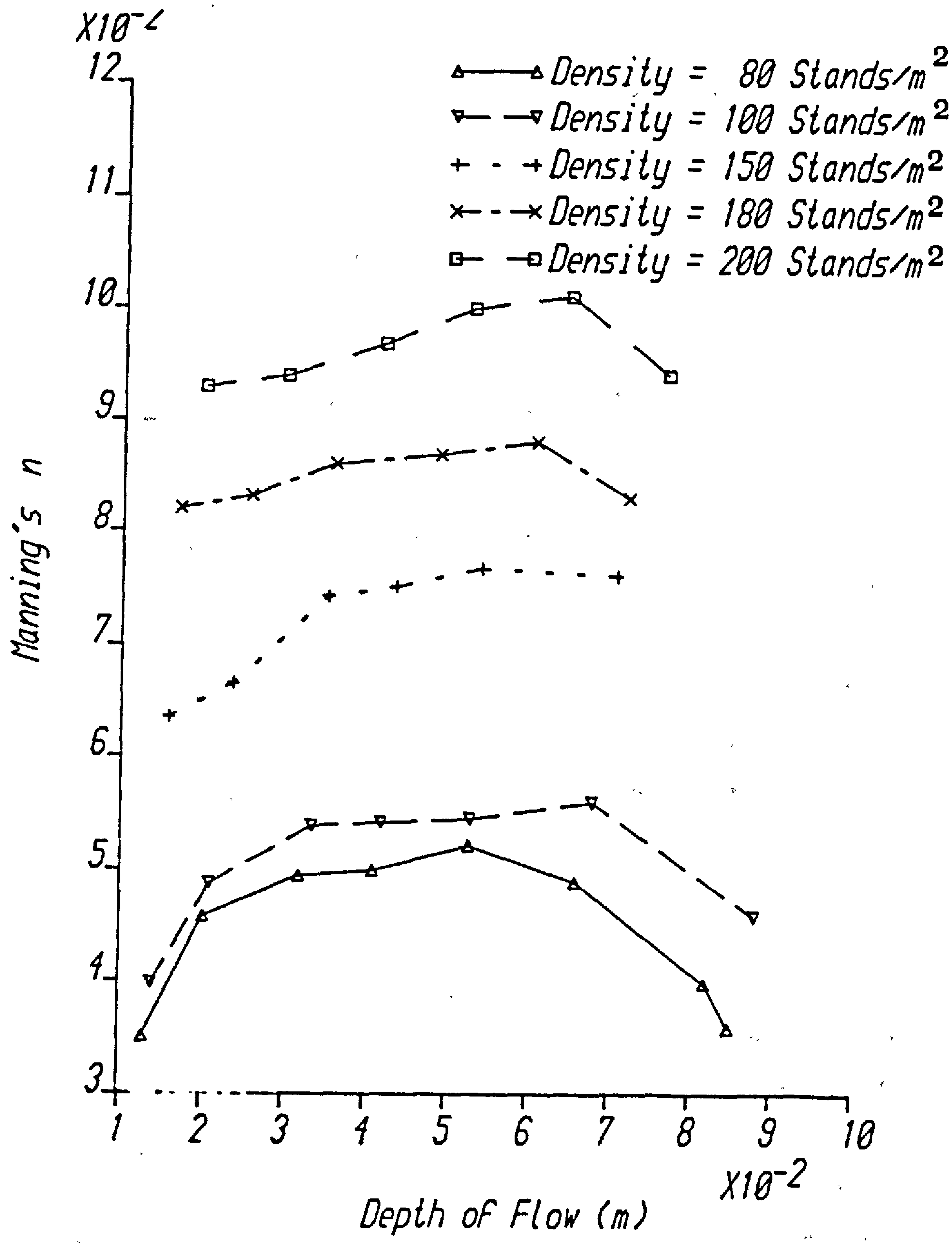


FIGURE 6.9 VARIATIONS OF CALCULATED MANNING'S n* WITH DEPTH OF FLOW AT CONSTANT 2° BED SLOPE IN VEGETATED CHANNELS

*Calculated from Manning's Equation (2.3)

as such, the effect of the vegetation on Manning's n in flows of higher magnitude could not be determined. The peak n values in all the vegetated flows were observed to occur just before the grass started bending, indicating a flow height in the vegetation, where a combination of the density and stiffness characteristics of the grass maximally retard flow. The observed pattern of n variation with flow in vegetation is significantly different from that observed on bare soil surfaces (Figures 6.3 and 6.4) where peak n values occur in the lowest flows because the roughness elements which retard flow are confined to the soil surfaces.

6.2.3 The Effect of Root Density on Bank Scour

The effect of roots on bank scour was investigated by determining the critical tractive forces (Equation 3.4) to which the bare sandy clay loam and the clay soils, with varying root densities, can be subjected before widespread scour commences. The vane shear strengths of the soils, at the time when the critical tractive forces were observed, were also measured in order to also determine the effect of soil shear strength on bank scour. The data are summarised in Table 6.4.

From this data, it can be seen that CTF and shear strength values have been determined for only 4 clay and 10 sandy clay loam samples with maximum root densities of 0.6 and 1.804 g/cm^3 respectively. This is because the flow capacity of the flume section was not high enough to produce CTF flow conditions when clay and sandy clay loam samples with higher root densities of 0.9 and 2.0 g/cm^3 respectively were tested.

TABLE 6.4: CRITICAL BANK TRACTIVE FORCE AND VANE SHEAR STRENGTH AT DIFFERENT ROOT DENSITIES

ROOT DENSITY (g/cm^3)	CRITICAL TRACTIVE FORCE (N/m^2)	VANE SHEAR STRENGTH (N/m^2)
	(A) CLAY SOIL	
Root-free (Control)	3.35	1.5
0.164	4.14	2.0
0.358	6.38	3.5
0.600	7.51	4.5
	(B) SANDY CLAY LOAM SOIL	
Root-free (Control)	0.827	0.0
0.100	2.360	0.5
0.677	3.821	1.5
0.777	4.136	2.0
0.956	5.830	2.5
1.1075	5.910	3.5
1.157	6.499	4.0
1.228	6.620	4.5
1.571	6.640	5.5
1.804	7.960	7.5

The data show that the root-free clay CTF value of 3.35 N/m^2 is much greater than the root-free sandy clay loam CTF of 0.827 N/m^2. This indicates, as expected, that the root-free sandy clay loam soil is more erodible than the root-free clay. In terms of flow retardance (Tables 6.2 and 6.3, Section 6.2.1.2), this is because the root-free clay soils retard flows more, and as such require flows of higher tractive force to erode them. Also, the CTF values of the root-permeated clay soils are similarly considerably higher, at comparable root densities, than those of the sandy clay loam soils. For instance, the CTF value of the clay with 0.6 g/cm^3 of roots (CTF = 7.51 N/m^2) is about double the CTF value of 3.82 N/m^2 for the sandy clay loam with root density of 0.677 g/cm^3.

For both soils, however, CTF values increase with the density of the roots in the soil. This indicates that increasing the root density of both soils increases their tractive/scour resistance. The root-free CTF values of 0.827 N/m^2 (sandy clay loam) and 3.35 N/m^2 (clay), shown in Table 6.4, are reasonably within the range of values published by Dunn (1959), 0.9 to 2.06 N/m^2 for channel bed soils "ranging from sand to thick silty clay," by Smerdon and Beasley (1961), 0.95 to 2.62 N/m^2 for "11 Missouri soils," and by Lane (1953) and Webber (1971), 2.0 N/m^2 for sandy loam. For all these data, however, direct comparisons with respect to soil type cannot be made with the root-free data in Table 6.4. Nevertheless, as the data in Table 6.4 show, for both soils used in this study, CTF values of soils permeated with only about 0.6 g/cm^3 of roots can be more than 100% higher than the CTF values of the root-free soils; indicating that the CTF values for vegetated conditions may not be entirely due to the effects of the vegetal elements but also partly due to the presence of roots in the soils.

Observations were made on the rate of scour on some of the samples for tractive forces greater than the critical values shown in Table 6.4. These observations showed that the root-free samples of both soils were very rapidly eroded by the flows greater than the critical. The scour holes produced by these flows deepened very rapidly leading to the collapse of masses of soil which almost immediately dispersed and produced very thick muddy flows. For the root-permeated samples, scour occurred less rapidly after the critical tractive flows and tended to occur mainly through the selective removal of soil aggregates, some of which were observed to adhere very firmly to the roots and rootlets in the soils, as they dangled in the flow.

In order to determine how increases in the root densities of the soils are related to scour/tractive resistance, the CTF values were correlated with and regressed on the corresponding root density values of the soils. The graphs of these relationships are shown in Figure 6.10. The graphs show that, for both soils, the relationship between CTF and root density is positive and linear. The very high correlation coefficients obtained for both relationships are highly significant at the 95% confidence level. These results indicate that for both soils, critical bank tractive forces increase linearly with the density of the roots in the soil.

The difference in the magnitudes of the intercept values of these relationships reflect the difference in the tractive resistance of the root-free samples of both soils already discussed. The magnitudes of the slope values of the two regression relationships indicate that critical tractive forces increase at a higher rate for a unit increase in root density in the clay than in the sandy clay loam. The difference in the magnitudes of the two slope values was statistically tested at the 95% confidence level (Gomez and Gomez, 1984). The computed t value for the difference between the two slope values, $t = 3.04$, was greater than the Table t value, at degree of freedom (df) = 10, of $t = 2.228$. This means that the two slope values are statistically significantly different. This implies that for both soils, a single regression equation cannot be used to explain the relationship between CTF and root density. These results mean that for each soil, the increase in CTF can be explained by the increase in the root densities in the soil but that root density is not a good

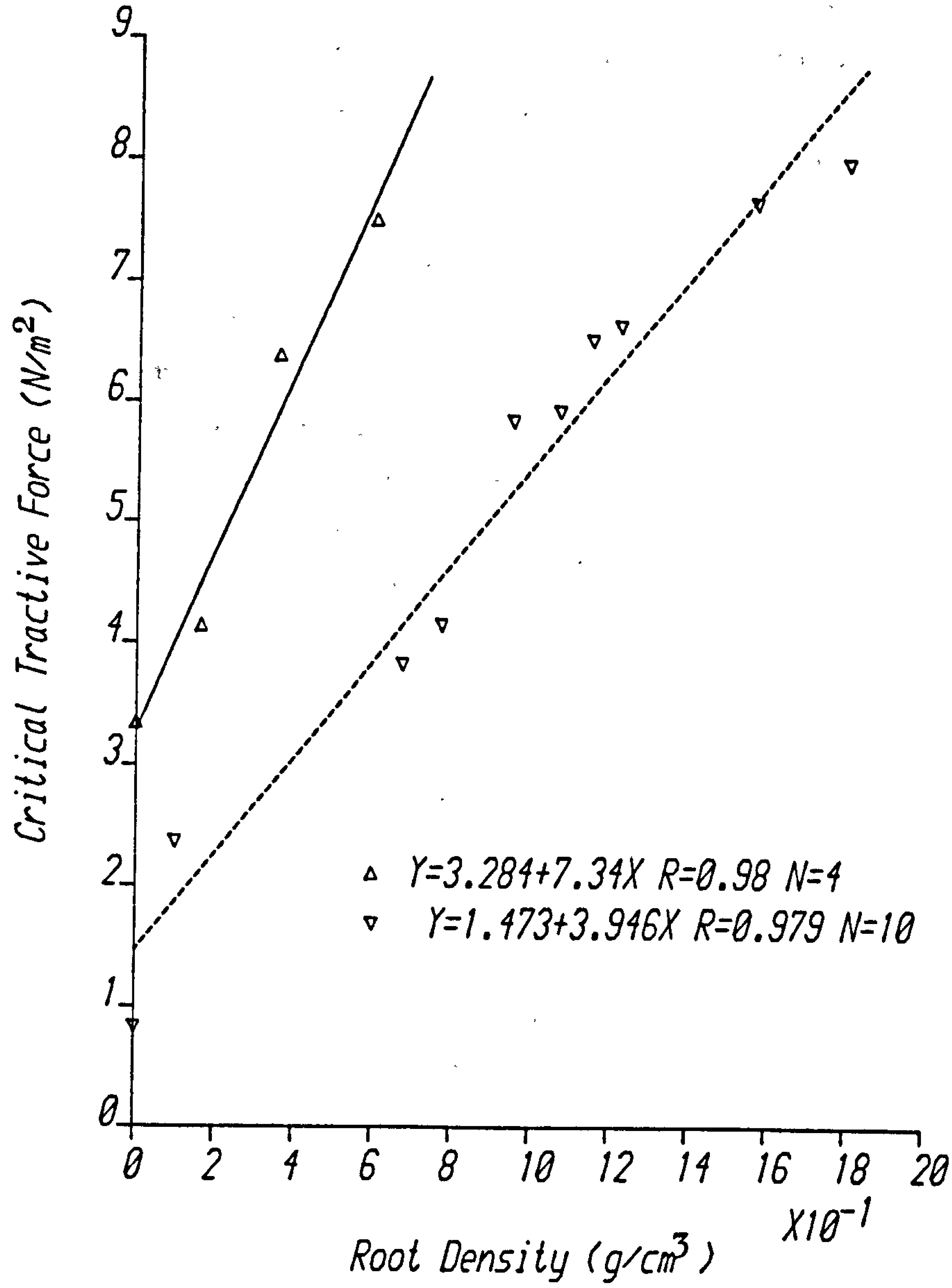


FIGURE 6.10 THE EFFECT OF ROOT DENSITY ON CRITICAL TRACTIVE FORCE (SANDY CLAY LOAM AND CLAY SOILS)

indicator of tractive resistance in both soils. This is probably because the scour resistance of soils may not be entirely dependent upon the flow retardance effects of roots in soils.

The data in Table 6.4 also show the vane shear strength of the soils when CTF conditions were observed. The data show that, for each soil, the CTF values increase with the shear strength of the soil. In order to determine how increases in the shear strength of the soils are related to tractive resistance, the CTF values of each soil were correlated with and regressed on the corresponding shear strength values. The graphs of the relationships are shown in Figure 6.11. These graphs show that for both soils, the CTF - shear strength relationships are linear and positive. The high correlation coefficients for both relationships are significant at better than the 95% confidence level. These results mean that, within the range of data collected, CTF increases linearly with increases in the shear strength of each soil.

The intercept value of the clay relationship does not represent the CTF for the case of Zero shear strength because the measured clay shear strength values range from only 1.5 to 4.5 kPa. The magnitudes of the slopes of the regression equations for both soils indicate that for a unit increase in shear strength, critical tractive forces increase at 1.4 N/m^2 in the clay and 0.936 N/m^2 in the sandy clay loam. The statistical significance of the difference between these slope values was tested at the 95% confidence level (Gomez and Gomez, 1984). The t-value computed for the difference between the two regression coefficients is $t = 1.357$. The Table t-value, at $df = 10$ is $t = 2.228$. Since the Table t is greater than the computed t, it is concluded that statistically, the slope values are not significantly different. The mean shear strength values of 2.875 kPa (clay) and 3.15 kPa (sandy clay loam) are also not significantly different at the 95% confidence level (Gregory, 1978).

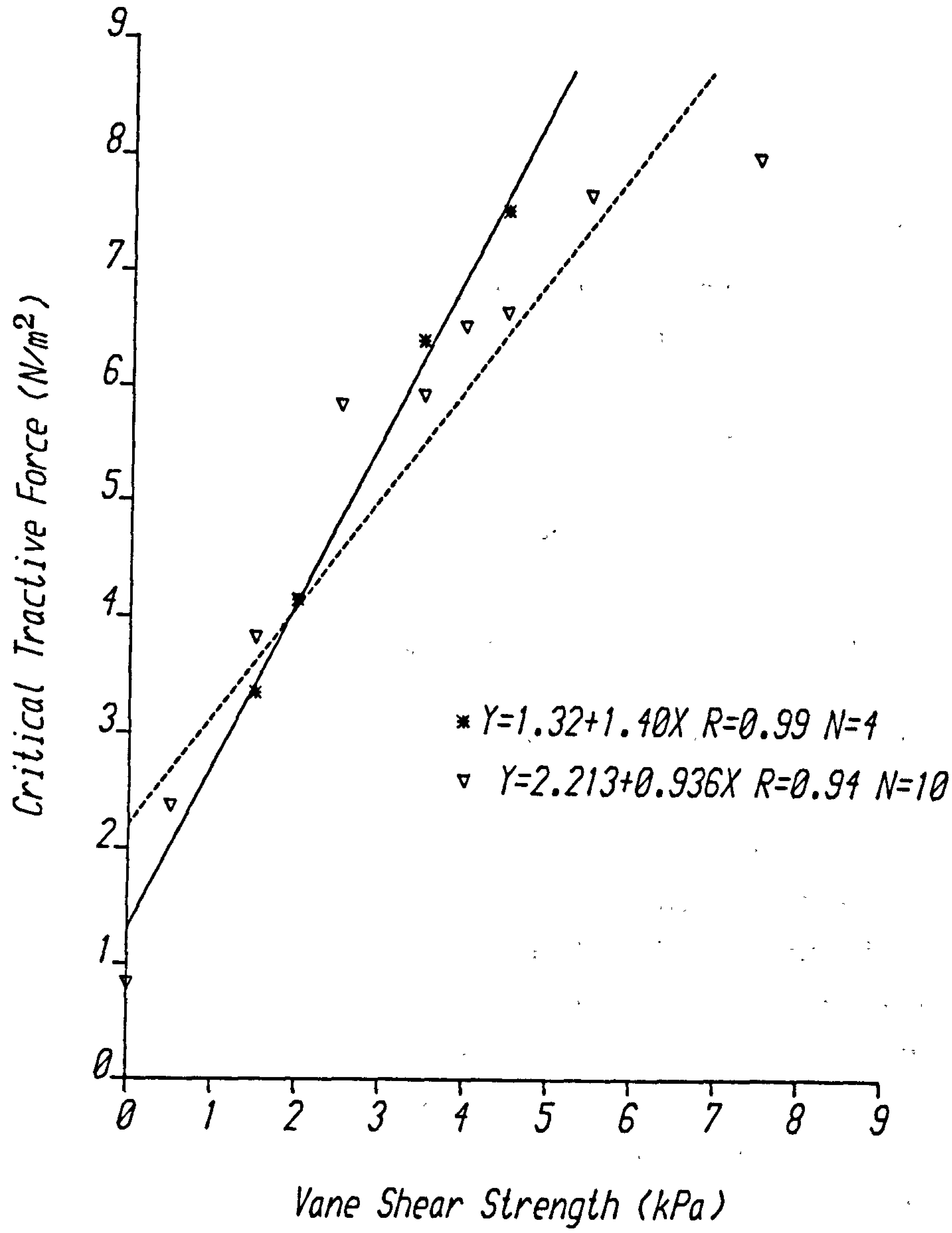


FIGURE 6.11 THE EFFECT OF SHEAR STRENGTH ON CRITICAL TRACTIVE FORCE (SANDY CLAY LOAM AND CLAY SOILS)

These results imply that a single regression equation can be used to describe the relationship between critical bank tractive force and vane shear strength for both soils. This can be interpreted to mean that tractive resistance can be predicted from the measured vane shear strength values of both soils. The data in Table 6.4 also reflect this very clearly. For instance, for the root-free clay soil with a shear strength of 1.5 kPa, the CTF value is 3.35 N/m^2; the sandy clay loam sample with a similar CTF value of 3.82 N/m^2 also has a shear strength value of 1.5 kPa. Such similarities in CTF values can be seen to occur among the sandy clay loam and clay samples with similar shear strength values.

The CTF - shear strength relationship for both soils is shown in Figure 6.12 and is described by a regression equation which shows that the CTF values of the soils increase by about 1.0 N/m^2 for a unit increase in shear strength (kPa). These results indicate that irrespective of the differences in soil and in root density, similar tractive forces are required to erode bare soils with similar vane shear strengths. This shows very clearly that although these soils have very different physical properties (Table 3.1), their scour erodibility is related mainly to their shear strength. As pointed out in sections 2.5.1 and 2.5.2, soil shear strength has not only been found to explain rill erosion (Rauws and Govers, 1988), inter-rill erosion (Watson and Laflen, 1986), and splash erosion (Al-Durrah and Bradford, 1981, 1982; Cruse and Larson, 1977; Schultz et al, 1975), it has also been correlated with the erosion potential of soils in channels (Flaxman, 1963). This finding therefore supports the proposal made in section 2.5 that the shear strength of soil is a good indicator of its scour erodibility.

6.2.4 <u>The Relative Effects of Vegetation Parameters on Bank Scour</u>

The results in section 6.2.2.3 have shown that increases in vegetation density considerably increase flow retardance in

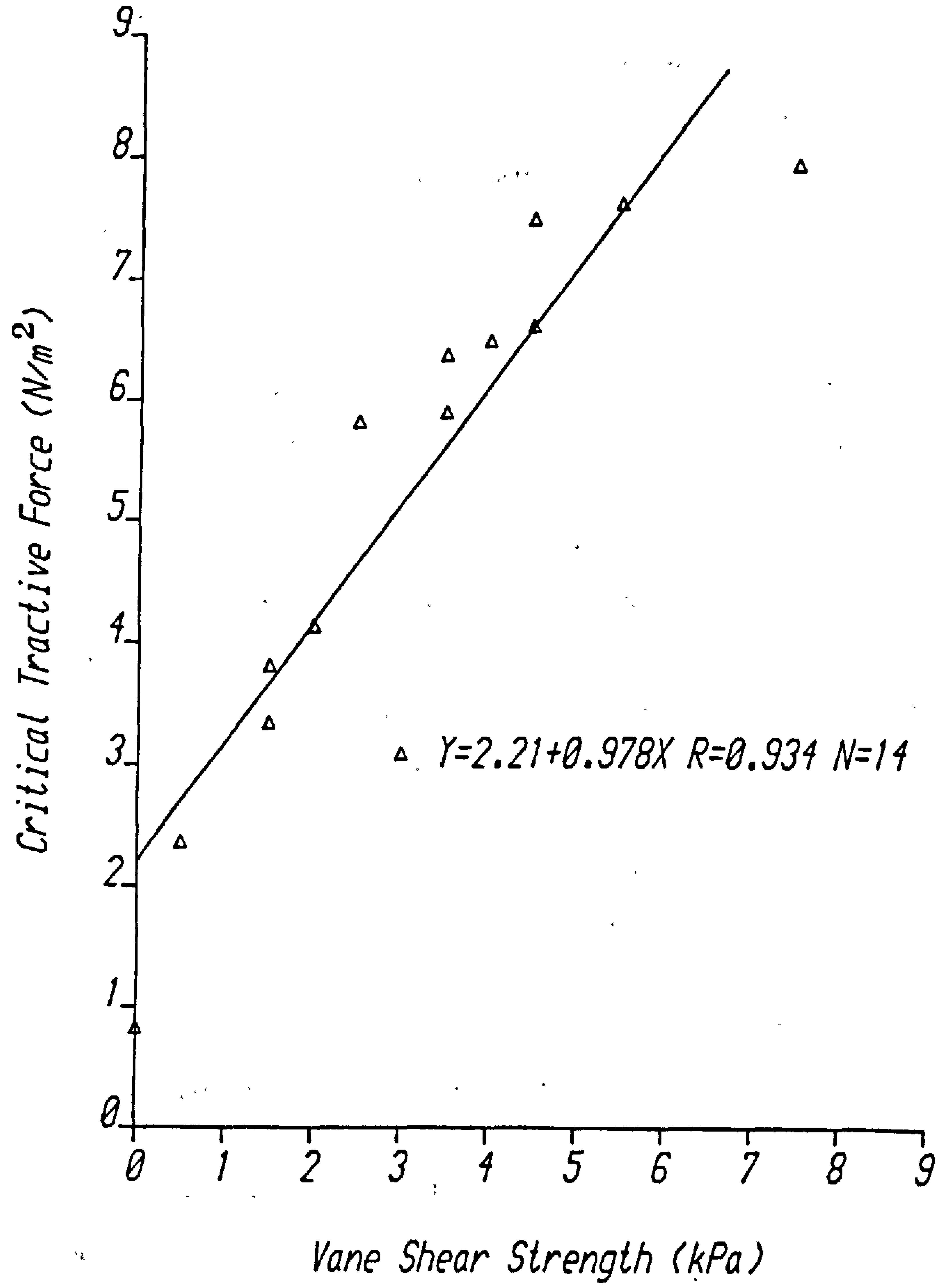


FIGURE 6.12 THE RELATIONSHIP BETWEEN CRITICAL TRACTIVE FORCE AND SHEAR STRENGTH OF SOILS

high flow depths that are below vegetal roughness heights. Also, the results of the effects of root density on flow retardance (Section 6.2.1.2) and on scour (Section 6.2.3) have shown that increases in the root density of soils can also considerably increase the flow and tractive resistance of root-permeated soils in channel banks. In this section, these results are considered together with a view to determining the relative effects of vegetation shoots and root-permeated soils on bank tractive forces which have been determined at varying channel flow depths for flows in five grass vegetation densities with similar root densities of 1.8 g/cm^3.

The total bank tractive forces (TTF) acting in the vegetated channel flows have been determined from Equation 3.4; these tractive force values represent the total channel bank tractive resistance. The tractive forces acting at the soil-water interface in these vegetated channel flows are calculated from Equation 3.5 for root-free and root-permeated soil conditions; these represent the tractive resistance of the root-free (TFs) and root-permeated (TFrs) soil conditions. As explained in Chapter 3.5.2, the maximum n_s and n_{rs} values of both soils are used in the computations of the bank tractive forces acting at the soil-water interface in the vegetated channel flows. For the sandy clay loam, $n_s = 0.00763$ and $n_{rs} = 0.0161$ at root density of 1.804 g/cm^3; for the clay $n_s = 0.0166$ but the maximum n_{rs} of 0.01895 is for a root density of 0.6 g/cm^3 (Table 6.1). Since the root density of the vegetated soils for which total tractive forces are determined is 1.8 g/cm^3, the TFrs values computed for the clay should be regarded as underestimates. The tractive force values, computed for each flow in each vegetation density, are expressed as a proportion of the total channel bank tractive force (TTF) and are summarised in Tables 6.5 and 6.6 for the clay and sandy clay loam conditions respectively.

These data show that in the vegetated channel flows, the total channel bank tractive resistance increases with depth of flow.

TABLE 6.5: THE RELATIVE TRACTIVE RESISTANCE OF ROUGHNESS COMPONENTS IN VEGETATED CHANNEL FLOWS IN CLAY SOIL CONDITIONS

VEGETATION DENSITY (Stands/m^2)	DEPTH OF CHANNEL FLOW (m)	TOTAL CHANNEL TRACTIVE RESISTANCE TTF (N/m^2) = 100%	PROPORTIONS OF TRACTIVE RESISTANCE CONTRIBUTED BY CHANNEL ROUGHNESS COMPONENTS				ROOT DENSITY (g/cm^3)
			ROOT-PERMEATED SOILS $\frac{TFrs}{TTF}$	ROOT-FREE SOILS $\frac{TFs}{TTF}$	ROOTS ONLY TFrs-TFs	SHOOTS ONLY TTF-TFrs	
80	0.013	3.10	0.2931	0.2249	0.0682	0.7069	1.8
	0.020	4.80	0.1704	0.1308	0.0396	0.8296	
	0.032	7.60	0.1466	0.1125	0.0341	0.8534	
	0.041	9.70	0.1436	0.1102	0.0334	0.8564	
	0.053	12.50	0.1318	0.1011	0.0307	0.8682	
	0.066	15.60	0.1231	0.0945	0.0286	0.8769	
	0.082	19.40	0.2244	0.1722	0.0522	0.7756	
	0.085	20.10	0.2771	0.2126	0.0645	0.7229	
						(81.12)*	
100	0.014	3.31	0.2267	0.1740	0.0527	0.7733	1.8
	0.021	5.00	0.1508	0.1157	0.0351	0.8492	
	0.034	7.92	0.1236	0.0949	0.0287	0.8764	
	0.042	9.93	0.1222	0.0938	0.0284	0.8778	
	0.053	12.53	0.1209	0.0928	0.0291	0.8791	
	0.068	16.10	0.1145	0.0879	0.0266	0.8855	
	0.088	20.80	0.1559	0.1196	0.0363	0.8441	
						(85.51)*	
150	0.016	3.74	0.0887	0.0681	0.0206	0.9113	1.8
	0.024	5.60	0.0810	0.0621	0.0189	0.9190	
	0.035	8.35	0.0650	0.0499	0.0151	0.9350	
	0.044	10.32	0.0638	0.0490	0.0148	0.9362	
	0.054	12.84	0.0611	0.0469	0.0142	0.9389	
	0.071	16.80	0.0622	0.0477	0.0145	0.9378	
						(92.97)*	
180	0.017	4.08	0.0534	0.0410	0.0124	0.9466	1.8
	0.026	6.10	0.0519	0.0398	0.0121	0.9481	
	0.036	8.51	0.0484	0.0372	0.0112	0.9516	
	0.049	11.60	0.0476	0.0365	0.0111	0.9524	
	0.061	14.42	0.0464	0.0356	0.0108	0.9536	
	0.072	17.10	0.0521	0.0400	0.0121	0.9479	
						(95.00)*	
200	0.020	4.73	0.0415	0.0319	0.0096	0.9585	1.8
	0.030	7.10	0.0406	0.0312	0.0094	0.9594	
	0.042	9.93	0.0383	0.0294	0.0089	0.9617	
	0.053	12.53	0.0360	0.0276	0.0084	0.9640	
	0.065	15.40	0.0352	0.0270	0.0082	0.9648	
	0.077	18.20	0.0406	0.0312	0.0094	0.9594	
						(96.13)*	

* Figures in brackets indicate average Percentage Tractive Resistance

TABLE 6.6: THE RELATIVE TRACTIVE RESISTANCE OF ROUGHNESS COMPONENTS IN VEGETATED CHANNEL FLOWS FOR SANDY CLAY LOAM CONDITIONS

VEGETATION DENSITY (Stands/ m^2)	DEPTH OF CHANNEL FLOW (m)	TOTAL CHANNEL TRACTIVE RESISTANCE TTF (N/m^2) = 100%	PROPORTIONS OF TRACTIVE RESISTANCE CONTRIBUTED BY CHANNEL ROUGHNESS COMPONENTS				ROOT DENSITY (g/cm^3)
			ROOT-PERMEATED SOILS $\frac{TFrs}{TTF}$	ROOT-FREE SOILS $\frac{TFs}{TTF}$	ROOTS ONLY TFrs-TFs	SHOOTS ONLY TTF-TFrs	
80	0.013	3.10	0.2116	0.0475	0.1641	0.7884	1.8
	0.020	4.80	0.1230	0.0276	0.0954	0.8770	
	0.032	7.60	0.1058	0.0238	0.0820	0.8942	
	0.041	9.70	0.1037	0.0233	0.0804	0.8963	
	0.053	12.50	0.0951	0.0214	0.0737	0.9049	
	0.066	15.60	0.0889	0.0200	0.0689	0.9111	
	0.082	19.40	0.1620	0.0364	0.1256	0.8380	
	0.085	20.10	0.2000	0.0449	0.1551	0.8000 (86.37)*	
100	0.014	3.31	0.1636	0.0368	0.1268	0.8364	1.8
	0.021	5.00	0.1088	0.0244	0.0866	0.8912	
	0.034	7.92	0.0892	0.0200	0.0692	0.9108	
	0.042	9.93	0.0882	0.0198	0.0684	0.9118	
	0.053	12.53	0.0873	0.0196	0.0677	0.9127	
	0.068	16.10	0.0827	0.0186	0.0641	0.9173	
	0.088	20.80	0.1125	0.0253	0.0872	0.8875 * (89.54)	
150	0.016	3.74	0.0640	0.0144	0.0496	0.9360	1.8
	0.024	5.60	0.0584	0.0131	0.0453	0.9416	
	0.035	8.35	0.0470	0.0105	0.0365	0.9530	
	0.044	10.32	0.0461	0.0103	0.0358	0.9539	
	0.054	12.84	0.0441	0.0099	0.0342	0.9559	
	0.071	16.80	0.0449	0.0101	0.0348	0.9551 * (94.93)	
180	0.017	4.08	0.0385	0.0087	0.0298	0.9615	1.8
	0.026	6.10	0.0374	0.0084	0.0290	0.9626	
	0.036	8.51	0.0350	0.0079	0.0271	0.9650	
	0.049	11.60	0.0343	0.0077	0.0266	0.9657	
	0.061	14.42	0.0335	0.0075	0.0260	0.9665	
	0.072	17.10	0.0376	0.0085	0.0291	0.9624 (96.40)*	
200	0.020	4.73	0.0300	0.0067	0.0233	0.9700	1.8
	0.030	7.10	0.0293	0.0066	0.0227	0.9707	
	0.042	9.93	0.0277	0.0062	0.0215	0.9723	
	0.053	12.53	0.0260	0.0058	0.0202	0.9740	
	0.065	15.40	0.0254	0.0057	0.0197	0.9746	
	0.077	18.20	0.0293	0.0066	0.0227	0.9707 (97.21)*	

*Figures in brackets indicate average Percentage Tractive Resistance

The proportion of this tractive resistance contributed by the root-permeated soils is higher than that contributed by the root-free soils. In the sandy clay loam soil (Table 6.6), the proportion of the total tractive forces resisted by the root-permeated soils is more than 400% higher than the very low tractive resistance of root-free soils; for the clay (Table 6.5), this increase is only 130%. This is because, as shown by the data in both Tables, the roots contribute as much as 78% of the tractive resistance of root-permeated sandy clay loam soil whilst contributing only 23% to the tractive resistance of the root-permeated clay soil. These results therefore indicate that the presence of roots increases the tractive resistance of root-free soils and that this increase is very considerable in the sandy clay loam soil.

The proportion of the total tractive resistance contributed by the root-permeated soils is at a maximum in low vegetation densities and decreases as vegetation density increases. For the clay soil, the maximum proportion of tractive resistance contributed by the root-permeated soils decreases from 29.31% in the grass vegetation density of 80 stands/m^2 to about 4% in the maximum vegetation density of 200 stands/m^2. For the sandy clay loam soils, the corresponding proportions are 21 to 3%. At the same time as root-permeated tractive resistance decreases, the proportion of tractive resistance due to the vegetation shoots increases with vegetation density from 70.69% to just over 96% in the clay, and from about 79% to just over 97% in the sandy clay loam. These results show that even in the lowest vegetation density used in this study, vegetation shoots are responsible for resisting most of the channel bank tractive forces of the flowing water. Reference to the data in Table 6.7 shows that this protective ability of vegetation shoots would increase with increasing vegetation density but that the increase is greatest when the increase in vegetation density is from bare conditions, and decreases with subsequent increases in vegetation density.

TABLE 6.7: INCREASES IN TRACTIVE RESISTANCE OF VEGETATION SHOOTS FOR INCREASES IN VEGETATION DENSITY

VEGETATION DENSITY (Stands/ m^2)	AVERAGE PERCENTAGE TRACTIVE RESISTANCE (SHOOTS)	PERCENTAGE INCREASE in VEGETATION DENSITY (RELATIVE TO 80 STANDS)	INCREASE IN % RESISTANCE	PERCENTAGE INCREASE IN VEGETATION DENSITY (RELATIVE to 100 STANDS)	INCREASE in % RESISTANCE	PERCENTAGE INCREASE IN VEGETATION DENSITY (RELATIVE TO 150 STANDS)	INCREASE in % RESISTANCE	PERCENTAGE INCREASE IN VEGETATION DENSITY (RELATIVE TO 180 STANDS)	INCREASE in % RESISTANCE
				CLAY SOIL					
80	81.12	-	-	-	-	-	-	-	-
100	85.51	25	4.39	-	-	-	-	-	-
150	92.27	88	11.15	50	6.76	-	-	-	-
180	95.00	125	13.88	80	9.49	20	2.73	-	-
200	96.13	150	15.01	100	10.62	33	3.86	11	1.13
				SANDY CLAY LOAM SOIL					
80	86.37	-	-	-	-	-	-	-	-
100	89.54	25	3.17	-	-	-	-	-	-
150	94.93	88	8.56	50	5.39	-	-	-	-
180	96.40	125	10.03	80	6.86	20	1.47	-	-
200	97.21	150	10.84	100	7.67	33	2.28	11	0.81

For instance, in Table 6.7, column 2 shows that the average percentage tractive resistance by shoots, for the vegetation densities shown in Column 1, ranges from 81.12% to 96.13% in the clay and from 86.37% to 97.21% in the sandy clay loam conditions. Columns 3 and 4 show that increasing the vegetation density of 80 stands by 25, 88, 125 and 150% (Column 3) would increase the tractive resistance by only about 4, 11, 14 and 15% in the clay, and by 3, 9, 10 and 11% in the sandy clay loam respectively (Column 4). The other columns (6, 8 and 10) show similarly decreasing percentage increases in protection for increasing vegetation densities from 100, 150 and 180 stands. It is known however, that if an additional objective is to also maintain high channel flow capacities, then excessive increases in vegetation density can be undesirable as they would considerably lower channel flow capacities (Bache and MacAskill, 1981).

The results in Tables 6.5 and 6.6 also show that in each vegetation density, the maximum proportion of total tractive resistance contributed by the root-permeated soils occurs at the lowest flow depths. These maximum proportions of tractive resistance values are highest in the lowest vegetation density where, at a low flow depth of 0.013m, root-permeated soils account for up to 21.16% and 29.31% of the total tractive forces in the sandy clay loam and clay soil conditions respectively. As flow depths increase up to a depth before vegetation bending by flows starts, the proportion of tractive resistance due to root-permeated soils decreases to a minimum whilst vegetative tractive resistance increases to a maximum. After vegetation bending, further increases in flow depth result in decreasing vegetal resistance and, consequently, in increases in the tractive forces actually acting at the soil surface. Although not verified, because the capacity of the flume section was reached, it would seem that as flow depth continues to increase after vegetation bending, the magnitude of the tractive forces resisted by the vegetation shoots would continue to decrease whilst the tractive forces acting on the root-permeated soil surfaces would continue to increase in magnitude until they become critical and then scour the soil. The high flows at which these forces could become critical would then depend mainly on the density of roots in the soil. The depths of flow at which this would have occurred in each of the vegetation densities investigated could not, however, be determined because increasing flow depths beyond those used in this study (Appendix 6.2A) would have increased the flow depths in the vegetation to levels which would have overflowed the flume section.

These results indicate that increasing vegetation densities will increase the protection of bank materials against scour and that the protection is highest when the vegetation density increases are from bare soil conditions. The results also indicate that at high flow depths before vegetation bending starts, and especially in high vegetation densities, channel bank soils are protected from scour mainly because of the very high tractive resistance of the vegetal elements in the flows. For instance, at the flow depth of 0.065m in the vegetation density of 200 stands/m^2 (Root density = 1.8 g/cm^3), the total channel bank tractive force is 15.4 N/m^2. From the data in Table 6.6, it could be seen that 97.46% of this tractive force (15.00 N/m^2) is resisted by the vegetation shoots whilst only 2.54% (0.400 N/m^2) actually impinges on the root-permeated soil surfaces. As the data in Table 6.4B (Section 6.2.3) show, this tractive force magnitude of 0.40 N/m^2 is almost 20 times less than the estimated critical value of 7.96 N/m^2 which should be exceeded for scour to occur in the sandy clay loam soil permeated with 1.8 g/cm^3 of roots.

Also, the relatively high tractive resistance of root-permeated soils observed to occur at low channel flow depths would evidently increase with decreasing flow depth such that, at very low flows, as occur in surface irrigation channels, the tractive resistance of root—permeated soils could be very significant if vegetation densities are much lower than used in this study, and if the random and parallel vegetation patterns are used instead of the staggered pattern used in this study (Hartley, 1980). For such conditions, grasses that produce a very dense root mat could be grown at very low densities so that tractive flows can be resisted by the root-permeated soils whilst the low foliage density would not greatly decrease the capacity of the channel.

6.3 Summary of Findings

The results of the effects of vegetation roots and shoots on flow have shown that flows on bare (root-free and root-permeated) soil surfaces are mainly supercritical whilst in vegetal elements, the flows are mainly subcritical. In terms of flow retardance, it is found that for all bare soils, roughness mainly retards the initial low flows in contact with the soil surfaces; subsequent flow increases are therefore not retarded by the soil surface roughness. Consequently, Manning's n values were observed to generally decrease, as expected, with increases in flow depth. For each soil, it is found that increases in root density are accompanied by increases in flow retardance; the increases observed for the sandy clay loam soils are greater than those observed for the clay. The precise mechanisms involved in achieving these increases in n values are not known but it is suggested that differences in form and stable aggregate size roughness characteristics between the sandy clay loam and clay soils can partly explain the observed differences in the magnitudes of retardance effects between the two soils. In vegetated soils, the pattern of increasing and then decreasing n with increasing flow, was as expected for the low to intermediate flow depths achieved in the flume.

In evaluating the effects of roots on bank scour in terms of critical tractive forces, it was found that for each soil, a strong, positive and linear relationship exists between root density and CTF. But it was found that similar root density soils had critical tractive forces of significantly different magnitudes for the two soils. Consequently, root density was not found to be a good indicator of the erodibility of the soils. The shear strength of the soils was found to correlate well with increases in CTF. In this case, shear strength was found to be a good indicator of the erodibility of the soils. This is because, irrespective of differences in soil type and root density, soils with similar shear strength values were found to have similar CTF values.

In determining the relative effects of the roots and shoots on channel bank scour, it was found that vegetation shoots are responsible for resisting most of the channel bank tractive forces especially during high flows in which the vegetation remains erect. The protective ability of the vegetation shoots was found to increase with vegetation density although this also has the effect of reducing channel flow capacity. It was also found that the presence of roots in soils does contribute significantly to tractive resistance especially at low flows and in low vegetation densities. It is suggested that at very high flows, when the vegetation is flattened and the tractive resistance of vegetation shoots is minimal, the role of the roots in the soil could become critical in protecting the soils from scour. This however needs to be verified by experiments in which flows of a sufficient magnitude to scour the root-permeated soils could be generated.

CHAPTER SEVEN

THE EFFECT OF ROOT DENSITY ON BANK STABILITY

Channel banks are commonly eroded by gravitational forces tending to cause slope failure by slumping. Although usually neglected in the study of bank erosion processes (Morgan, 1986), there is evidence in the literature to show that erosion by slumping can be the dominant erosion process along many channel banks (See Chapter 2.1). When using vegetation as a means of bank protection, it is the roots that are likely to play a more direct role in stabilising the bank materials. There is no evidence in published literature to suggest that this role has been investigated before. The aim of this Chapter therefore is to determine how increases in the density of roots in saturated bank materials influence the stability of channel bank slopes with respect to slumping.

7.1 Bank Stability Analysis

In general, a slope fails by shear when, along any potential failure surface, the shear force is greater than the shear strength of the slope material. The stability of a channel bank therefore depends on a delicate balance between the shear strength of the soil and the shearing forces acting on the soil. This balance of forces is usually expressed in terms of a factor of safety Fs, defined as

$$Fs = \frac{\text{The Shear Strength along the failure surface}}{\text{The sum of the shear forces that promote sliding along the failure surface}}$$

A factor of safety of unity would indicate incipient failure, a factor of safety of less than unity indicates instability and a factor of safety greater than unity would indicate stability.

Stability analysis may be undertaken in a number of ways (Bishop and Morgenstern, 1960; Golder and Ward, 1950; Lambe and Whitman, 1969; Nash, 1987; Taylor, 1937; Terzaghi and Peck, 1967). In this study the total stress equilibrium method for the ($\phi = 0$) soil condition, based on Janbu's (1954) generalised procedure of slices, is used to assess the effect of grass root density on the stability of a conveyance channel bank in the clay soil used. Janbu's method is chosen mainly because it can be rapidly and easily applied and, for short term stability, it is considered to be one of the most widely used (Bishop and Morgenstern, 1960) and most accurate total stress slope stability methods (Wright et al, 1973).

7.1.1 Procedure

The procedure, for the ($\phi = 0$) soil condition used in this study involves the calculation of a factor of safety (Fs) from the formula (Janbu, 1954):

$$Fs = \frac{N.C_u}{BD.H} \qquad (7.1)$$

Where:

N = A stability number

C_u = The undrained cohesion of the soil (lbs/sq.ft)

BD = The bulk density of the soil (lbs/cu.ft)

H = The height of the bank (ft) (See Figure 2.1)

The stability number is obtained from a prepared graph (Appendix 7.1: from Janbu, 1954), when the bank slope (B) (Figure 2.1) and the depth factor (d) are known. The depth factor is calculated from (Janbu, 1954):

$$d = \frac{D}{H}$$

Where:

D = The depth from the toe to the firm base (See Appendix 7.1)

H is as defined above.

The prepared graph (Appendix 7.1) shows than (N) depends only on the slope angle, for slopes steeper than about 60^o, in which case the critical slip circle intersects the toe. For slopes flatter than 60^o, the critical slip circle may intersect either the base, the toe or the slope (above the toe), depending on the values of (B) and (D) (Janbu, 1954). In this study, the stability analysis for all bank slope conditions is undertaken for a depth factor of d = 0, so as to exclude the possibility of base failure (Figure 2.1) which could involve bank material at depths which may not be penetrated by grass roots (Greenway, 1987). For stability against toe failure, the toe slope is probably the most critical zone that should be strengthened because it is a site of potential instability due to scour or basal removal (Bache and MacAskill, 1984; Hudson, 1986; Lawler, 1986; Little et al, 1982; Richards and Lorriman, 1987; Thorne and Tovey, 1981). Consequently, maintaining or increasing the strength of the toe, even down to the shallow depths that would be penetrated by grass roots, is important for the stabilisation of the banks against toe failure.

7.2 Data for Bank Stability Analysis

The purpose of the stability analysis is mainly to determine how grass root density effects on the shear strength of the bank materials affect stability in terms of factors of safety. According to Janbu's procedure, for ($\phi = 0$) soils, the factor of safety for a given channel boundary condition is a function of the soil shear strength (undrained cohesion) and bulk density parameters, and the channel bank slope and height (Figure 2.1). The shear strength and bulk density parameters determined for the clay soil, collected from the crests of the banks of a conveyance channel, are presented in Table 7.1 for root-free and root-permeated conditions. The geometric properties of this channel were determined. The section of the channel from which bank slope and height measurements were made was straight and 30 m long. The banks, covered in mixed grasses and shrubs, appeared to be stable and showed no evidence of recent slumping. The maximum bank height measured was 1.5m. The most frequently occurring slope angles determined by means of an Abrey level were 30^{o}, 40^{o} and 53^{o}. These data are also summarised in Table 7.1.

The cohesion - root density values in this table show that at zero matric potential, cohesion increases from a root-free value of 3.58 kPa to 20.61 kPa in soils with 3.0 g/cm^3 of roots. This represents a cohesion increase of 476% due to the effects of the roots produced after about 20 weeks growth of Loretta grass. The effects of

TABLE 7.1: SOIL PARAMETERS AND BANK GEOMETRY DATA FOR STABILITY ANALYSIS

Root Density g/cm^3	Undrained Cohesion (Cu) kPa	lbs/sq.ft	Bulk Density lbs/cu.ft	Channel Bank Geometry
Root-free	3.580	74.786	96.142	Bank Slopes:
0.085	4.900	102.361	103.821	30°; 40°, 53°;
0.170	7.383	154.231	107.754	90° (assumed)
0.230	8.022	167.580	120.759	Bank Height:
0.400	10.490	219.136	135.643	1.5m (4.92 ft)
0.700	12.833	268.081	158.759	Assumed: 2.25 m
0.750	12.981	271.173	160.623	(7.38 ft)
1.050	14.236	297.390	175.331	
1.900	17.316	361.731	201.767	
2.000	17.476	365.074	203.643	
2.200	18.510	386.674	206.701	
3.000	20.610	430.523	224.124	

such cohesion increases on changes in the stability of channel bank slopes have not been previously investigated. However, Gray and Leiser (1982, in Figure 3.26, P. 52) have shown that the stability of a saturated soil mantle is very sensitive to increases in cohesion. Also, Singh (1970) has observed that a variation of 50% in the value of cohesion may result in an appreciable variation in the factor of safety of hillslopes. For a 420% increase in the shear strength of a silty clay loam due to alfalfa roots, Waldron (1977) has calculated increases in the factor of safety of up to 550% for hillslope conditions.

In order to determine the effect of root density on the stability of the channel banks, factors of safety have been calculated using Equation 7.1 for the measured channel geometries, for root-free (bare) conditions for comparison with factors of safety calculated for a range of root density (vegetated) conditions. In order to determine how root density effects on factors of safety might change if bank heights and slopes increased, factors of safety have also been calculated for an assumed 50% increase in bank height and for assumed vertical slopes, using the same range of root density conditions as those used for the measured bank geometries. The results are presented in Appendix 7.2 and summarised in Table 7.2 for some root density conditions, including those up to which the factors of safety of the measured slope values indicate stability.

7.3 Discussion of Results

7.3.1 The Effect of Root Density on Factors of Safety

The data in Table 7.2 and Appendix 7.2 show that, as expected, at all root density treatments, increases in bank slope and height lead to decreases in the factors of safety of banks against sliding. The variation of Fs values with root density shows that increasing the root density from the root-free bank condition leads to increases in cohesion and, consequently, to increases in the factors of safety of the banks. The root-free Fs values for the 1.5m high bank conditions show that only the bare bank with the relatively gentler 30° slope angle is likely to be stable (Fs = 1.23); the 40° bank is likely to be unstable (Fs = 1.08), whilst the 53° and the assumed vertical bank slopes

Table 7.2

THE EFFECT OF ROOT DENSITY ON CHANNEL BANK FACTORS OF SAFETY (CLAY SOIL)

Root Density g/cm^3	Bank Height m	Bank Slope degrees	Undrained Cohesion (Cu) kPa	Factors of Safety Fs
Root-free (Control)	1.50	30	3.58	1.23
		40		1.08
		53		0.90
		90*		0.61
	2.25*	30		0.82
		40		0.72
		53		0,60
		90*		0.40
0.085	1.50	30	4.90 (37%)	1.56 (27%)
		40		1.36 (26%)
		53		1.14 (26%)
		90*		0.77 (26%)
	2.25*	30		1.04 (27%)
		40		0.91 (28%)
		53		0.76 (27%)
		90*		0.51 (28%)
0.170	1.50	30	7.383 (100%)	2.27 (85%)
		40		1.98 (83%)
		53		1.66 (84%)
		90*		1.11 (82%)
	2.25*	90*		0.74 (85%)
3.00	1.50	30	20.61 (476%)	3.04 (147%)
		40		2.65 (145%)
		53		2.23 (148%)
		90*		1.50 (146%)
	2.25*	90*		0.99 (148%)

* Assumed Values

Values in brackets show increases of Fs relative to root-free (bare) conditions.

are likely to be very unstable (Fs 0.9 and 0.61 respectively).

However, for an addition of only 0.085 g/cm^3 of grass roots to the bare banks, the results show that the root-free soil cohesion is increased by 1.2 kPa, from 3.58 to 4.90 kPa. This 37% increase in soil cohesion, which is due to a root density produced during less than four weeks vegetal growth, results in about 27% increases in the Fs values of all bank slopes. This percentage increase in Fs values at this bank height (1.5m) results in stable Fs values for all but the assumed vertical bank slope (Table 7.2). For root density increases of 0.17 g/cm^3, the results show that soil cohesion is increased by about 100% from 3.58 to 7.383 kPa. With this magnitude of increase in cohesion, the Fs value of even the vertical bank slope is very substantially increased by 82% to a level which indicates stability (Fs = 1.11).

The results show that in general, root permeated channel bank conditions are more stable against failure than root-free (bare) bank conditions and that for the given soil and bank height conditions, small increases in cohesion due to grass root density can substantially increase the factors of safety and hence the stability of soils in saturated channel bank conditions with up to 53^{o} slope angles. For vertical channel bank conditions at this height however, the results show that a minimum of 100% cohesion increase is required for stability against toe and slope failures.

When the bank height is increased by 50% to 2.25m, the root-free Fs values at all slope angles decrease as expected, and indicate instability. This means that, as expected, the deepening of saturated channel banks at this height and at these slope angles could be expected to lead to widespread instabilities with respect to bank failure. When the root-free cohesion of these higher banks is increased by root densities of 0.085 g/cm^3, the Fs values of the banks increase as expected, with the percentage increases being similar to those observed for similar root density increases at the lower 1.5 m high banks (Table 7.2). At this bank height however, even the Fs value of the least slope (30^{o}) only indicates imminent instability, with the steeper bank slopes indicating instability. However, for a 100% increase in root-free cohesion due to root density increases of 0.17 g/cm^3, the results show that the Fs values of all the measured bank slopes are increased by about 85% (Appendix 7.2) to values indicating stability. At this 2.25m high bank however, the Fs value of the assumed vertical bank condition (Fs 0.74) does not indicate stability even though the factor of satety, relative to the root-free condition, is increased by 85%. Even at the highest root density of 3.0 g/cm^3, at which the root-free cohesion increase of 476% increases the factor of safety by 148%, the resulting Fs of 0.99 still does not indicate conditions of stability.

These results show that for relatively low root densities of 0.17 g/cm^3, which can be achieved by four weeks of vegetal growth and which increase cohesion by about 100%, the factor of safety of the 2.25 m high banks, with slope angles of up to 53^o, can be increased to stable levels. The results also show, however, that even the highest observed root density of 3.0 g/cm^3, produced during 20 weeks vegetal growth, may not provide enough shear strength to stabilise saturated vertical channel banks at this height. These results imply, therefore, that it is possible to stabilise even vertical channel banks by vegetative means if banks are low (1.5 m) but that if the banks are high (2.25 m), it may not be possible to stabilise such slopes by only vegetative means without also adopting bank shaping to reduce bank slope angles.

It should be pointed out that these results are only indicative of the experimental conditions simulated. The observed grass root effects may or may not increase slope stability as much as implied by the calculated increases in factors of safety because the root density effects along the infinitely different possible sliding surfaces may not be the same as the ones usedin these calculations. However, the assumption here is that, for the observed increases in cohesion due to the grass root density increases of the soil, the calculated increases in the Fs values of the root-permeated soils relative to the root-free could be expected. The results could therefore have a direct application to shallow slope failures and to toe failures along low homogeneous and cohesive channel banks.

7.4 Summary of Findings

The results in this Chapter indicate that for saturated homogeneous cohesive bank conditions, apart from the 30^{o} bank slope at 1.5 m high, all the root-free bank slopes at both 1.5 and 2.25 m heights do not indicate stability, with the steeper banks being more unstable, as expected, than the gentler slope banks. The results also show that for 1.5 m high banks, only 0.085 g/cm^3 of roots are required to stabilise bank slopes up to 53^{o}. For vertical banks at this height (1.5m), and for bank slopes of up to 53^{o} and at 2.25 m high, only 0.17 g/cm^3 of roots are required to achieve stability. For vertical banks at 2.25 m high, stability is not achieved even when cohesion is increased by 476% from 3.58 to 20.61 kPa by 3.0 g/cm^3 of grass roots.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

This study was concerned with the effects of vegetation root and shoot densities on the scour and slump stability of cohesive sandy clay loam and clay bank materials. Scour was assessed by means of the tractive force approach in laboratory flume experiments. Flows on the bare root-free and root-permeated samples ranged from depths of 3mm at velocities of 0.7 m/s to 30 mm at 1.3 m/s; in the vegetated samples, the flows ranged from depths of 10 mm at velocities of 0.3 m/s to 90 mm at 1.0 m/s. All flows were at the same flume channel bed slope of 2^{o}. Slump stability was assessed for the clay soil by determining the factors of safety for cohesion increases due to root density, using Janbu's (1954) total stress stability method. An assessment was also made of the effects of root density on the strength characteristics of the bank materials at saturation and at moisture contents decreasing from saturation to plastic limit. The findings and their implications are discussed within the framework of the limitations of the study.

8.1 Conclusions

The main conclusions arrived at from this study are as follows:

i) Increases in root density do not affect the established exponential pattern of shear strength increase with soil drying between saturation and plastic limit of the root-free soils. As expected, roots increase the magnitude of the shear strength of soils at all the moisture contents investigated; at saturation, this increase is linear, whilst at plastic limit it is logarithmic. This difference is due to the magnitude of the rooting effect being greater at plastic limit than at saturation. The results of the shear strength - moisture content relationships further show that root-permeated soils exhibit considerable shear strength at high moisture contents at which root-free soils exhibit flowage; also, the shear strength values of the root-permeated soils continue to increase with soil drying at low moisture contents at which the root-free soils cease to exhibit plastic characteristics and become brittle, and crumble. The results of comparing the rooting effects in the soils indicates that roots increase the shear strength of different soils by different amounts; roots increase the shear strength of the clay soils by about twice as much as they do the shear strength of the sandy clay loam soils.

ii) The results of the bulk density - moisture content relationships indicate that roots do not affect the established linear increase in the dry bulk density of soils with soil drying. However, small amounts of roots in the clay soil used increase the magnitude of the bulk density values whilst high root densities actually decrease rather than continue to increase the dry bulk density values. Relative increases in the bulk density values of root-free soils are generally interpreted to mean relative increases in shear strength values. This, however, may not be the case for soils with increasingly high densities of roots. In this case, it seems that although higher root density soils will have higher shear strength values, the lower shear strength soils of lower root densities could have relatively higher dry bulk density values than soils with higher root densities.

iii) Previous studies and discussions on the effect of roots on shear strength assume that the effect is to increase cohesion only, with little or no effect on soil friction. The results from this study show that at saturation, it may be justifiable to regard the effect of roots in clay soils as being mainly to increase cohesion because of the very small changes in friction effected by root density increases. However, in the sandy clay loam soils, roots are important in increasing significantly both the cohesional and frictional components of shear strength.

iv) The results of the flume evaluations of the scour resistance of bare root-free and root-permeated soils indicate that channel banks are most vulnerable to scour when rooting effects due to vegetal growth are absent. In terms of critical tractive forces, the resistance of bank materials to scour increases linearly with root density and vane shear strength. However, the bank scour resistance of both the sandy clay loam and clay soils was characterised better by shear strength than by root density. A single relationship was established that could predict the scour resistance of both soils from their vane shear strength values. Soil shear strength can therefore be regarded as an effective measure of the erodibility of root-free and root-permeated soils with respect to the scour erosion of channel banks.

v) The comparisons of the relative protection from scour due to the root-free and root-permeated soils indicate that roots considerably increase the scour resistance over that of root-free soils. Increases of more than 400% in scour resistance were observed for soils with 1.8 g/cm^3 of roots. This finding indicates the need to take into account the presence of roots in the soil when assessing the scour resistance potential of vegetated channels. It also suggests a need to consider rooting density characteristics as an important factor in selecting grasses for bank protection against scour.

Comparing the protection due to vegetation shoots and root-permeated soils confirms the dominance of the protective ability of vegetation shoots over root-permeated soils for flows in which the vegetation is erect or bending. Nevertheless, in low flows through low vegetation densities, root-permeated soils contribute significantly to the protection of bank materials from scour. However, additional flow experiments involving flows up to the critical are required to clarify the relative effect of root density on scour in flows in which the vegetation is prone.

The results further confirm that increasing vegetation density tends to increase scour resistance. The results however indicate that it is the initial introduction of vegetation into root-free bank conditions that is most importante because it results in the greatest increase in resistance against scour. Since high increases in vegetation density also reduce the capacity of the channel, it is suggested that, for bank protection against scour, in channels that are also required to maintain given discharges, a combination of low vegetation densities of grasses that develop a very high root mat should be used.

vi) The results of the effect of roots on bank stability confirm that what is known about the effect of tree roots on the stability of hillslopes will also apply to grass roots in saturated clay channel bank conditions; namely that roots increase the stability of channel banks, through significant increases in the shear strength of the soils for very small increases in root density. The results, however, indicate that the effects of even very high increases in root density may not increase the factors of safety of saturated channel banks, that are very steep and high, to stable levels. For such bank conditions to be stabilised therefore, it may be necessary to combine vegetation and bank shaping.

8.2 Implications

The fact that root-free soils possess no measurable vane shear strength at saturation whilst root-permeated soils exhibit increasing shear strength, implies that the saturation moisture content of root-permeated soils is much higher than that of root-free soils. Also, the fact that at plastic limit, the shear strength of root-free soils decreases whilst those of the root-permeated soils continue to increase with further soil drying implies that the plastic limit moisture content value of the root-permeated soils is lower than that of the root-free soils. These implications, taken together, suggest that plasticity index determinations for root-free soil conditions are probably not representative of root-permeated soil conditions.

The consistent increase in the values of the regression coefficients determined for the increasing root density samples in the shear strength - moisture content relationships could imply that the rate at which shear strength increases with soil drying, increases with the density of roots in the sandy clay loam soils. For the clay, the values could imply that the root-permeated soils possess a higher rate of shear strength increase with soil drying than the root-free soils. However, the pattern of change in the regression coefficients for the root-permeated clay soils is not clearly defined.

The finding that roots significantly increase both the cohesional and frictional strength characteristics of sandy clay loam soils has important implications for the assumption, frequently made in determining the effect of roots on stability, that roots contribute mainly to the cohesion of soils. The results of this study have demonstrated that such an assumption may be valid only for clay soils and not for sandier soils.

This study has shown that increases in root density considerably increase the flow and tractive resistance of root-free soils. Previous studies using root-free n values to assess scour resistance in vegetated channels could therefore have considerably underestimated the scour resistance potential of the root-permeated vegetated channel surfaces. This finding therefore implies that there is a need to take into account the presence of roots in bank soils when assessing the scour resistance potential of soils in vegetated channel banks. The result also implies that the rooting density characteristics of grass should be regarded as an important criterion when selecting grasses for bank protection. In so doing, grasses should be selected that can provide a very dense root mat for even low shoot densities, so that banks can be protected from scour whilst, especially at high flows, maintaining or not significantly reducing the channel flow capacity.

The results of the critical tractive force experiments show that the scour resistance of soils is characterised better by vane shear strength than by root density increases. This finding has a very important implication for the use of soil shear strength as a useful index of the erodibility of soils by scour.

The bank stability results imply that grass vegetation roots alone can be completely relied upon to stabilise even vertical bank slopes against slumping, provided the banks are low. The short growth period indicated for the vegetation roots to bring about the stability levels found implies that it is plants that establish quickly and produce very dense root mats that are particularly useful in stabilising channel banks. The results, however, also imply that vegetative methods alone may not stabilise high and steep channel banks.

8.3 Limitations of the Study

The shear strength - root density relationships were investigated mainly to determine the effect of root density on the stability of channel bank slopes with respect to scour and slumping. For stability with respect to slumping, the shear strength increases determined were for very shallow soil depths of up to 5 cm. Strictly therefore, the stabilising effects of roots examined in this study can be said to apply only to very shallow rather than deep-seated failures. However, as early as after three weeks of vegetation growth, roots were observed to have extended to the bottom of all the sample boxes. Although not measured, the densities of the roots at the bottom of sample boxes, with vegetation growth periods of at least four weeks, seemed higher than at the 5 cm depth at which strength determinations were made. This suggests that were it not for the shallow 15 cm deep sample boxes used, the rooting effects would have extended deeper than 15 cm after four weeks. Since it is not known how much deeper these effects would have extended, and whether or not the magnitude of the effects would have uniformly increased to those depths, it is concluded that the root stabilising effects observed can be applicable to depths of down to 15 cm. As pointed out in Chapter 7.1.1., stabilising the toe to a depth of 15 cm can be very critical for the stabilisation of the rest of the bank slope against toe failure for which the analysis was undertaken.

Another limitation had to do with the scour experiments being conducted in a rigid-bottom rather than a false-bottom flume, for only one slope and for varying vegetation densities with similar rather than varying root densities. Because the flume had a rigid bottom, flows could not be made to pass directly over the sample surfaces. Consequently, a test section was constructed so that flows could pass on the sample surfaces. This not only considerably reduced the maximum flow that the flume could generate over the higher test surface, but it also reduced the maximum flow depth that could be accommodated from 31 cm to less than 10 cm. The reduction in the flow which could be generated on the higher flow section meant that in the critical tractive force experiments on bare root-free and root-permeated soils, the maximum flow generated was not of sufficient magnitude to achieve CTF flow conditions on sandy clay loam soils with root densities greater than 1.8 g/cm^3, and on clay soils with root densities greater than 0.6 g/cm^3. This meant that the effects of higher root densities in clay soils on flow retardance are not known. This led to the underestimation of the relative contribution of roots in clay soils to the total scour resistance in vegetated samples which had root densities of 1.8 g/cm^3.

The reduction in the maximum flow depth that the higher flow section could accommodate also meant that the effects of vegetation shoot density on scour resistance could not be determined for the very high flows necessary for the achievement of CTF flow conditions. Consequently the relative effects of vegetation root/shoot density on scour at CTF flows could not be determined.

All the flow experiments were carried out for only one channel bed slope and, in the vegetated flow experiments, for only one root density, mainly because of the constraints of time. Consequently, it is not known from this study what the effects of changes in channel slope will be on the scour resistance determined for bare root-free and root-permeated, and vegetated flow conditions.

8.4 Proposals for Further Study

From the results of this study, the following are proposed for further investigation so as to improve our understanding of the contribution of roots to shear strength, scour protection and bank stability.

i) Research should be undertaken to determine the effect of root density increases on the rate of wetting, drying and plasticity index characteristics of soils.

ii) For the clay soils used, high increases in root density were observed to lead to lower, rather than the expected higher, dry bulk density values. This relationship should be determined for sandier soils in order to determine whether or not rooting effects on the dry bulk density of soils are dependent on the sandiness of the soil, since increases in soil friction are theoretically associated with increases in bulk density.

iii) This study has shown that although roots may mainly affect the cohesion with very little effect on the friction of clay soils, for the sandy clay loam, the effect is to increase significantly both cohesion and friction. This difference in the effect of roots on the friction of the two soils is believed to be mainly due to differences in the sandiness of the soils. However, it will be necessary to verify this by determining the effect of roots on the frictional characteristics of soils with varying sandiness so as to determine the minimum sandiness of soils below which roots may not significantly affect changes in frictional strength.

iv) In this study, it is found that root density increases the flow retardance of different soils by different amounts, the actual reasons for this are not however known. It is therefore proposed that studies be undertaken to verify this finding and the reasons for it for a wider range of soil types so that the rooting factor in scour protection in different soils can be better understood.

v) Also, for a better understanding of the relative contribution of roots to scour protection, it is necessary to determine the relative contribution of root-permeated soils to scour resistance in deeper flow conditions than undertaken in this study and especially when the vegetation is prone so its contribution to scour protection is minimal.

vi) In this study, the observed shear strength increases due to roots were mainly explained in terms of physical mechanisms. Future studies should therefore investigate whether there are chemical mechanisms, such as the role of root exudates, through which roots increase the shear strength of soils.

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APPENDIX 4.1(a)

DATA FOR VANE SHEAR STRENGTH VARIATIONS WITH MOISTURE CONTENT SANDY CLAY LOAM SOIL

ROOT-FREE (CONTROL)

MOISTURE CONTENT (%)	SHEAR STRENGTH (kPa)
30.01	0.0
28.52	0.5
27.56	1.0
24.09	2.0
23.67	2.2
23.00	2.5
18.32	4.8
14.00	6.5
11.11	11.2
10.80	12.2
10.50	12.4
10.00	25.0
9.81	19.0
8.70	5.0

ROOT DENSITY = 0.20 g/cm^3

MOISTURE CONTENT (%)	SHEAR STRENGTH (kPa)
32.67	0.0
31.95	1.0
27.32	2.0
23.28	2.8
21.87	3.4
19.73	4.0
18.29	5.0
17.85	6.0
17.89	7.0
16.22	8.2
15.49	10.0
14.62	12.5
13.58	14.5
13.12	18.0
10.28	26.5
8.91	30.5
7.82	34.0
7.10	37.0
7.00	10.5

ROOT DENSITY = 0.50 g/cm^3

MOISTURE CONTENT (%)	SHEAR STRENGTH (kPa)
28.80	1.5
26.41	2.0
24.01	4.0
20.36	5.0
20.29	7.0
18.54	8.0
17.79	11.0
15.32	11.5
14.47	14.5
14.43	15.0
12.60	16.0
11.28	18.0
10.81	19.0
10.64	20.0
9.65	30.0
9.45	31.0
8.19	36.0
6.02	45.0

ROOT DENSITY = 0.90 g/cm^3

MOISTURE CONTENT (%)	SHEAR STRENGTH (kPa)
31.59	1.5
30.00	2.0
28.52	3.5
27.56	4.0
25.01	7.0
22.40	10.0
20.03	11.5
17.98	16.0
15.42	20.0
12.50	28.5
10.20	33.0
8.70	42.0
8.00	57.0

APPENDIX 4.1(a) (Continued)

MOISTURE CONTENT (%)	SHEAR STRENGTH (kPa)	MOISTURE CONTENT (%)	SHEAR STRENGTH (kPa)
ROOT DENSITY = 1.30 g/cm^3		ROOT DENSITY = 1.80 g/cm^3	
31.98	3.0	33.54	4.5
38.59	5.1	32.78	6.0
26.67	6.0	27.51	8.0
25.06	7.0	25.75	8.8
22.84	10.0	24.71	10.0
22.56	10.5	23.86	11.5
22.29	11.0	23.82	12.0
19.59	13.0	22.52	14.0
17.32	16.0	19.71	15.0
17.09	23.0	19.38	21.0
14.95	32.0	17.17	30.0
12.16	44.0	14.46	34.0
7.11	56.0	11.10	40.0
6.96	70.0	10.80	50.0
		10.40	63.0
		10.02	78.0
ROOT DENSITY = 1.50 g/cm^3			
29.70	4.0		
29.18	5.0		
29.11	5.5		
25.96	7.0		
25.80	9.0		
23.94	10.0		
22.73	12.0		
22.04	12.5		
18.39	18.0		
17.00	25.0		
14.42	32.0		
11.23	35.0		
10.00	46.0		
9.38	54.5		
9.00	61.0		
8.50	70.0		

APPENDIX 4.1(a) (Continued)

CLAY SOIL

ROOT-FREE (CONTROL)

MOISTURE CONTENT (%)	SHEAR STRENGTH (kPa)
70.17	0.0
65.05	0.5
62.66	1.5
61.20	2.0
57.83	3.0
56.12	3.5
51.90	5.0
47.26	7.0
43.45	10.0
42.93	11.5
42.56	12.0
38.02	16.0
35.05	20.0
34.13	21.5
33.10	24.0
32.00	27.87
26.83	22.0
20.01	13.0

ROOT DENSITY = 0.20 g/cm^3

MOISTURE CONTENT (%)	SHEAR STRENGTH (kPa)
73.90	2.0
68.30	3.0
61.42	4.5
56.05	6.0
51.25	7.0
50.18	7.5
46.41	10.0
40.54	17.0
39.52	17.9
38.56	19.5
37.29	21.0
36.54	24.0
31.27	32.0
26.85	36.5

ROOT DENSITY = 0.56 g/cm^3

MOISTURE CONTENT (%)	SHEAR STRENGTH (kPa)
71.10	4.0
64.41	5.0
55.30	7.0
55.21	9.0
49.04	12.0
46.35	14.0
43.96	17.0
37.55	25.0
36.73	27.0
32.50	34.0
30.91	36.0
30.20	37.0
25.05	44.0
23.24	49.0
22.28	55.0

ROOT DENSITY = 0.70 g/cm^3

MOISTURE CONTENT (%)	SHEAR STRENGTH (kPa)
68.86	4.0
64.85	5.5
63.51	6.0
62.42	7.0
62.08	7.5
58.19	9.5
51.45	13.0
41.35	21.0
38.74	25.6
38.57	27.9
32.35	39.5
30.91	41.9
27.54	52.0
23.17	65.0
21.59	85.5

APPENDIX 4.1(a) (Continued)

MOISTURE CONTENT (%)	SHEAR STRENGTH (kPa)
ROOT DENSITY = 1.20 g/cm^3	
69.86	7.5
65.65	9.0
58.11	11.5
55.38	12.5
54.50	13.0
52.99	15.0
48.36	18.5
44.64	22.5
42.62	25.5
38.33	31.0
35.93	36.5
34.44	39.5
29.05	52.0
28.96	56.0
27.95	66.0
26.19	80.0
ROOT DENSITY = 1.50 g/cm^3	
66.56	9.5
63.74	10.5
58.09	13.0
55.87	16.0
49.25	21.0
48.08	23.0
39.96	37.0
36.96	45.5
29.86	65.0
29.31	74.0
27.54	85.5
27.13	86.0
23.17	109.0
20.42	130.0+

MOISTURE CONTENT (%)	SHEAR STRENGTH (kPa)
ROOT DENSITY = 1.80 g/cm^3	
67.69	10.0
61.20	12.0
59.21	13.0
56.86	15.5
53.93	17.0
44.55	28.0
39.20	42.0
34.69	56.0
26.96	88.0
25.72	96.0
23.31	118.0
22.41	130.0+
ROOT DENSITY = 2.10 g/cm^3	
74.83	8.5
65.25	11.5
61.71	13.0
59.26	14.0
56.18	17.0
54.14	18.5
47.50	25.0
43.57	40.0
40.68	55.0
35.30	85.0
31.04	110.0
25.29	130.0+

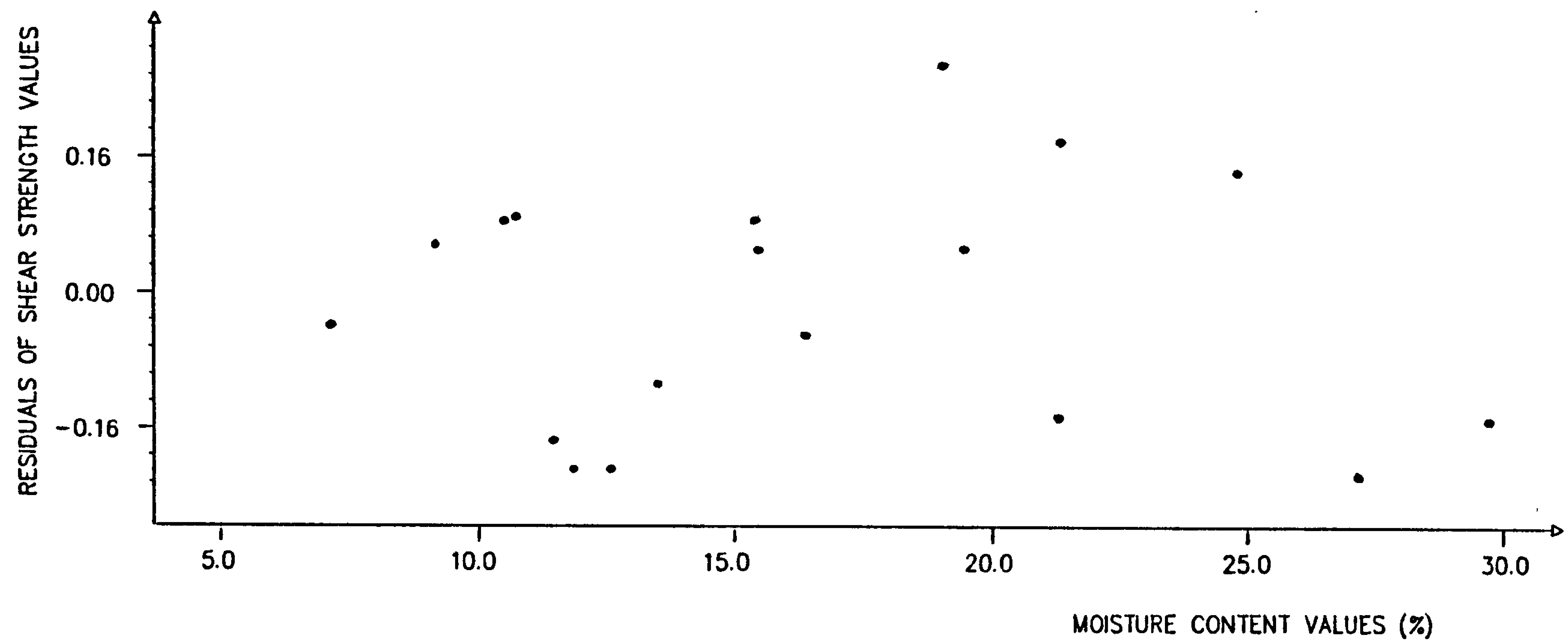
APPENDIX 4.1 (b)

DATA FOR DRY BULK DENSITY - MOISTURE CONTENT RELATIONSHIPS (CLAY SOIL)

MOISTURE CONTENT %	BULK DENSITY g/cm³	MOISTURE CONTENT %	BULK DENSITY g/cm³
ROOT FREE - CONTROL		ROOT DENSITY = 1.20 g/cm³	
61.56	0.95	56.88	0.970
54.83	0.98	55.35	1.053
45.54	1.00	49.96	1.060
41.55	1.01	40.99	1.080
38.35	1.01	38.33	1.095
36.45	1.03	33.79	1.110
33.52	1.05	32.76	1.115
29.03	1.06	17.32	1.310
ROOT DENSITY = 0.20 g/cm³		ROOT DENSITY = 1.50 g/cm³	
64.26	0.95	55.84	0.970
61.08	0.97	50.84	1.023
59.83	1.00	46.96	1.060
58.35	1.00	32.74	1.115
56.47	1.01	30.46	1.180
44.02	1.05	28.02	1.210
28.00	1.10	21.14	1.224
		17.49	1.260
ROOT DENSITY = 0.56 g/cm³		ROOT DENSITY = 1.80 g/cm³	
60.00	1.07	55.34	1.002
55.00	1.09	47.36	1.037
45.00	1.13	39.71	1.051
35.00	1.18	36.65	1.097
29.00	1.20	31.66	1.125
35.00	1.21	25.08	1.147
		22.75	1.184
		15.89	1.220
ROOT DENSITY 0.70 g/cm³		ROOT DENSITY = 2.10 g/cm³	
57.00	1.09	54.06	1.011
54.00	1.11	49.51	1.052
47.00	1.14	39.17	1.086
42.00	1.15	33.61	1.147
36.00	1.16	28.09	1.168
34.00	1.19	21.43	1.182
21.00	1.30	15.43	1.210

APPENDIX 4.2

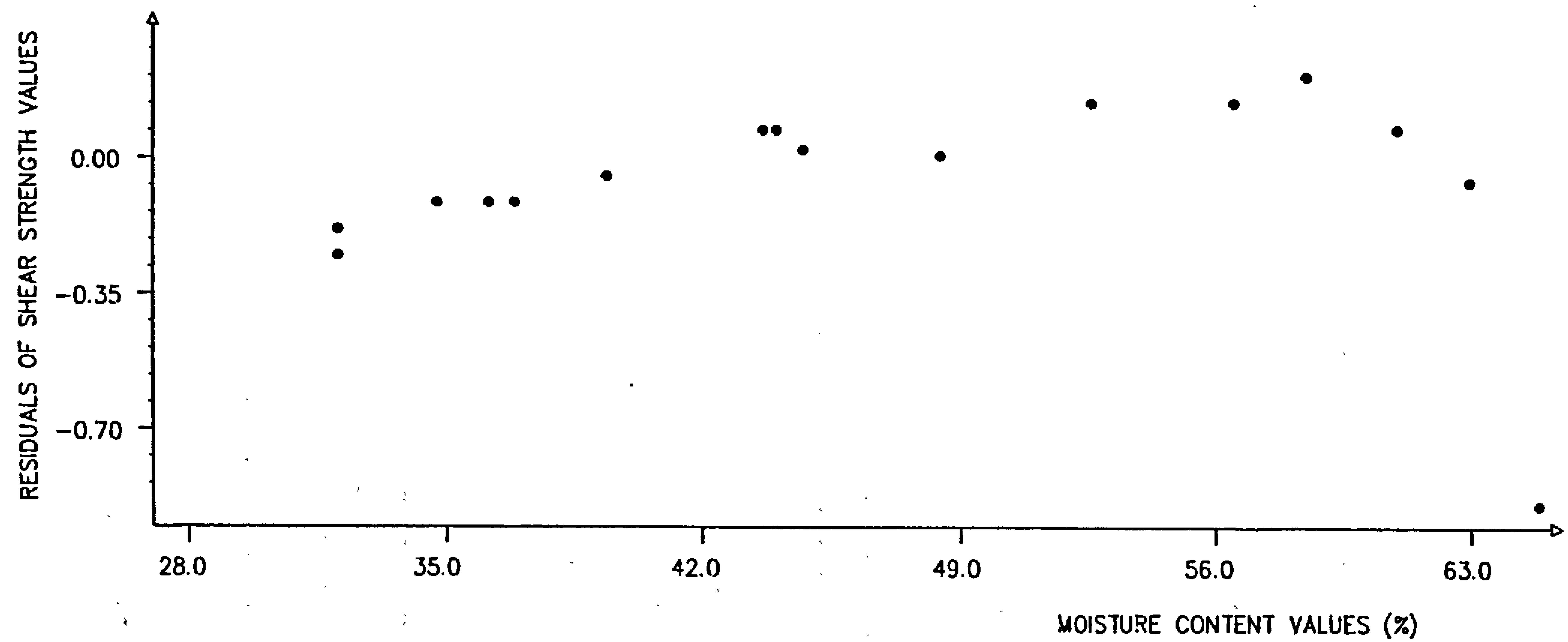
GRAPHS SHOWING TYPICAL NORMAL AND NON-NORMAL PLOTS OF CONDITIONAL DISTRIBUTIONS AGAINST MOISTURE CONTENT



(A) NORMAL CONDITIONAL DISTRIBUTION - SANDY CLAY LOAM (ROOT DENSITY OF 0.5 g/cm^3)

APPENDIX 4.2 (Continued)

GRAPHS SHOWING TYPICAL NORMAL AND NON-NORMAL PLOTS OF CONDITIONAL DISTRIBUTIONS AGAINST MOISTURE CONTENT



(B) NON-NORMAL CONDITIONAL DISTRIBUTION - ROOT-FREE CLAY

APPENDIX 4.3

DATA FOR VANE SHEAR STRENGTH - ROOT DENSITY RELATIONSHIPS AT SATURATION AND PLASTIC LIMIT

	ROOT DENSITY g/cm^3	SOIL SHEAR STRENGTH (kPa) SATURATION	PLASTIC LIMIT
	SANDY CLAY LOAM SOIL		
		30% Moisture Content	10% Moisture Content
1	0.00	0.0	25.0
2	0.20	1.0	26.5
3	0.50	1.5	30.0
4	0.90	2.5	35.0
5	1.30	3.5	45.0
6	1.50	4.0	48.0
7	1.80	5.0	78.0
	CLAY SOIL		
		70% Moisture Content	30% Moisture Content
1	0.00	0.0	28.5
2	0.20	1.5	33.0
3	0.56	3.0	37.0
4	0.70	3.5	41.0
5	1.20	7.0	51.0
6	1.50	8.0	60.0
7	1.80	8.5	70.0
8	2.10	9.0	114.0

APPENDIX 5.1(a)

TORSIONAL SHEAR STRENGTH (s/s) DATA

SANDY CLAY LOAM SOIL

σ	SHEAR STRENGTH (kPa)		FRICTION (Degrees)		SHEAR STRENGTH (kPa)		FRICTION (Degrees)	
(kPa)	MEASURED	ESTIMATED*	CALCULATED	ESTIMATED*	MEASURED	ESTIMATED*	CALCULATED	ESTIMATED*
	ROOT-FREE (CONTROL)				ROOT DENSITY = 0.748 g/cm³			
0	2.06	1.96	-		10.90	10.80	-	
6	5.14	5.44	27.17		16.04	16.02	40.59	
12	9.26	8.92	30.96		20.98	21.24	40.03	
18	12.34	12.40	29.73		26.74	26.46	41.35	
			Av. 29.29	30.23			Av. 40.66	41.16
	Regression Equation:		s/s = 1.96 + 0.58σ		Regression Equation:		s/s = 10.80 + 0.87σ	
			r = 0.998 r² = 99.65%				r = 0.999 r² = 99.89%	
	ROOT DENSITY = 0.056 g/cm³				ROOT DENSITY = 0.926 g/cm³			
0	3.10	3.10	-		11.80	11.78	-	
6	7.40	7.39	35.65		17.28	17.00	42.41	
12	11.52	11.71	35.06		21.60	22.22	39.24	
18	16.04	16.03	35.71		27.77	27.44	41.67	
			Av. 35.47	35.59			Av. 41.11	41.04
	Regression Equation:		s/s = 3.074 + 0.72σ		Regression Equation:		s/s = 11.78 + 0.87σ	
			r = 0.999 r² = 99.97%				r = 0.998 r² = 99.58%	
	ROOT DENSITY = 0.125 g/cm³				ROOT DENSITY = 1.08 g/cm³			
0	4.40	4.60	-		12.34	12.30	-	
6	9.05	8.92	37.78		17.69	17.58	41.72	
12	13.57	13.24	37.39		22.62	22.86	40.59	
18	17.28	17.56	35.59		28.38	28.14	41.70	
			Av. 36.92	35.73			Av. 41.34	41.48
	Regression Equation:		s/s = 4.60 + 0.72σ		Regression Equation:		s/s = 12.30 + 0.88σ	
			r = 0.999 r² = 99.74%				r = 0.999 r² = 99.91%	
	ROOT DENSITY = 0.235 g/cm³				ROOT DENSITY = 1.147 g/cm³			
0	6.17	6.19	-		12.75	12.71	-	
6	10.70	10.75	37.05		18.10	17.99	41.72	
12	15.43	15.31	37.66		23.04	23.27	40.61	
18	19.74	19.87	37.01		28.79	28.55	41.70	
			Av. 37.24	37.14			Av. 41.34	41.49
	Regression Equation:		s/s = 6.19 + 0.76σ		Regression Equation:		s/s = 12.71 + 0.88σ	
			r = 0.999 r² = 99.97%				r = 0.999 r² = 99.92%	
	ROOT DENSITY = 0.395 g/cm³				ROOT DENSITY = 1.297 g/cm³			
0	8.00	8.03	-		13.57	13.45	-	
6	12.75	12.77	38.37		18.72	18.91	40.64	
12	17.69	17.51	38.92		24.27	24.37	41.72	
18	22.21	22.25	38.29		29.82	29.83	42.08	
			Av. 38.53	38.41			Av. 41.48	42.15
	Regression Equation:		s/s = 8.03 + 0.79σ		Regression Equation:		s/s = 13.45 + 0.91σ	
			r = 0.999 r² = 99.97%				r = 0.999 r² = 99.97%	

* Estimated from the respective root density regression equations

APPENDIX 5.1(a) (Continued)

σ (kPa)	SHEAR STRENGTH (kPa) MEASURED	SHEAR STRENGTH (kPa) ESTIMATED*	FRICTION (Degrees) CALCULATED	FRICTION (Degrees) ESTIMATED*	SHEAR STRENGTH (kPa) MEASURED	SHEAR STRENGTH (kPa) ESTIMATED*	FRICTION (Degrees) CALCULATED	FRICTION (Degrees) ESTIMATED*
	ROOT DENSITY = 1.446 g/cm^3				ROOT DENSITY = 1.811 g/cm^3			
0	14.19	14.13	-		15.01	14.87	-	
6	19.54	19.53	41.72		20.36	20.39	41.72	
12	24.68	24.93	41.16		25.50	25.91	41.16	
18	30.44	30.33	42.08		31.67	31.43	42.79	
			Av.41.65	41.93			Av.41.89	42.57
	Regression Equation: $s/s = 14.13 + 0.90\sigma$				Regression Equation: $s/s = 14.87 + 0.92\sigma$			
	$r = 0.999$ $r^2 = 99.95\%$				$r = 0.999$ $r^2 = 99.84\%$			
	ROOT DENSITY = 1.539 g/cm^3				ROOT DENSITY = 1.918 g/cm^3			
0	14.40	14.34	-		15.63	15.55	-	
6	19.74	19.74	41.67		20.98	21.01	41.72	
12	24.90	25.14	41.19		26.33	26.47	41.72	
18	30.65	30.54	42.08		32.09	31.93	42.44	
			Av.41.65	41.94			Av.41.96	42.35
	Regression Equation: $s/s = 14.34 + 0.90\sigma$				Regression Equation: $s/s = 15.55 + 0.91\sigma$			
	$r = 0.999$ $r^2 = 99.95\%$				$r = 0.999$ $r^2 = 99.97\%$			
	ROOT DENSITY = 1.674 g/cm^3				ROOT DENSITY = 2.100 g/cm^3			
0	14.60	14.50	-		16.25	16.29	-	
6	19.95	19.96	41.72		21.80	21.69	42.77	
12	25.09	25.42	41.16		26.94	27.09	41.70	
18	31.06	30.88	42.44		32.50	32.49	42.08	
			Av.41.77	42.26			Av.42.18	41.93
	Regression Equation: $s/s = 14.50 + 0.91\sigma$				Regression Equation: $s/s = 16.29 + 0.90\sigma$			
	$r = 0.999$ $r^2 = 99.90\%$				$r = 0.999$ $r^2 = 99.98\%$			
	ROOT DENSITY = 1.767 g/cm^3							
0	14.81	14.71	-					
6	20.16	20.17	41.72					
12	25.30	25.63	41.16					
18	31.26	31.09	42.42					
			Av.41.77	42.24				
	Regression Equation: $s/s = 14.71 + 0.91\sigma$							
	$r = 0.999$ $r^2 = 99.90\%$							

CLAY SOIL

σ (kPa)	MEASURED	ESTIMATED*	CALCULATED	ESTIMATED*	MEASURED	ESTIMATED*	CALCULATED	ESTIMATED*
	ROOT-FREE (CONTROL)				ROOT DENSITY = 0.085 g/cm^3			
0	3.70	3.58	-		4.94	4.90	-	
6	4.11	4.28	3.9		6.58	6.70	15.29	
12	4.94	4.98	5.9		8.64	8.51	17.14	
18	5.76	5.68	6.5		10.28	10.32	16.52	
			Av.5.4	6.7			Av.16.3	16.8
	Regression Equation: $s/s = 3.58 + 0.117\sigma$				Regression Equation: $s/s = 4.90 + 0.301\sigma$			
	$r = 0.99$ $r^2 = 97.96\%$				$r = 0.99$ $r^2 = 99.78\%$			

* Estimated from the respective root density regression equations.

APPENDIX 5.1(a) (Continued)

σ (kPa)	SHEAR STRENGTH (kPa) MEASURED	SHEAR STRENGTH (kPa) ESTIMATED*	FRICTION (Degrees) CALCULATED	FRICTION (Degrees) ESTIMATED*	SHEAT STRENGTH (kPa) MEASURED	SHEAT STRENGTH (kPa) ESTIMATED*	FRICTION (Degrees) CALCULATED	FRICTION (Degrees) ESTIMATED*
	ROOT DENSITY = 0.170 g/cm³				ROOT DENSITY = 1.050 g/cm³			
0	7.40	7.38	-		14.40	14.24	-	
6	9.26	9.32	17.22		15.43	15.72	9.70	
12	11.31	11.25	18.05		17.28	17.20	13.50	
18	13.18	13.18	17.74		18.72	18.68	13.50	
			Av.17.70	17.90			Av.12.20	13.90
	Regression Equation: s/s = 7.38 + 0.322 σ; r = 0.99 r² = 99.96%				Regression Equation: s/s = 14.24 + 0.247 σ; r = 0.99 r² = 98.94%			
	ROOT DENSITY = 0.230 g/cm³				ROOT DENSITY = 1.900 g/cm³			
0	7.82	8.02	-		17.48	17.32	-	
6	10.28	10.08	22.29		18.51	18.59	9.74	
12	12.34	12.14	20.64		19.54	19.87	9.74	
18	13.99	14.20	18.92		21.39	21.15	12.26	
			Av.20.62	18.90			Av.10.60	12.00
	Regression Equation: s/s = 8.02 + 0.343 σ; r = 0.99 r² = 99.23%				Regression Equation: s/s = 17.32 + 0.213 σ; r = 0.99 r² = 97.58%			
	ROOT DENSITY = 0.400 g/cm³				ROOT DENSITY = 2.000 g/cm³			
0	10.28	10.49	-		17.68	17.48	-	
6	12.34	12.11	18.95		18.51	18.71	7.90	
12	13.99	13.73	17.18		19.74	19.95	9.74	
18	15.22	15.35	15.35		21.39	21.18	11.65	
			Av.17.16	15.35			Av. 9.80	11.64
	Regression Equation: s/s = 10.49 + 0.27 σ; r = 0.99 r² = 98.75%				Regression Equation: s/s = 17.48 + 0.206 σ; r = 0.99 r² = 97.85%			
	ROOT DENSITY = 0.700 g/cm³				ROOT DENSITY = 2.200 g/cm³			
0	12.75	12.83	-		18.51	18.51	-	
6	14.40	14.36	15.38		19.54	19.54		
12	16.04	15.88	15.33		20.57	20.57		
18	17.28	17.41	14.13		21.60	21.61		
			Av.14.90	14.24			9.70	9.74
	Regression Equation: s/s = 12.83 + 0.254 σ; r = 0.99 r² = 99.57%				Regression Equation: s/s = 18.51 + 0.172 σ; r = 0.99 r² = 99.99%			
	ROOT DENSITY = 0.750 g/cm³				ROOT DENSITY = 3.000 g/cm³			
0	12.96	12.98	-		20.57	20.61	-	
6	14.40	14.54	13.50		21.60	21.58	9.74	
12	16.45	16.10	16.22		22.62	22.54	9.69	
18	17.48	17.66	14.10		23.45	23.51	9.09	
			Av.14.60	14.60			Av.9.51	9.10
	Regression Equation: s/s = 12.98 + 0.26 σ; r = 0.99 r² = 98.59%				Regression Equation: s/s = 20.61 + 0.161 σ; r = 0.99 r² = 99.75%			

*Estimated from the respective root density regression equations.

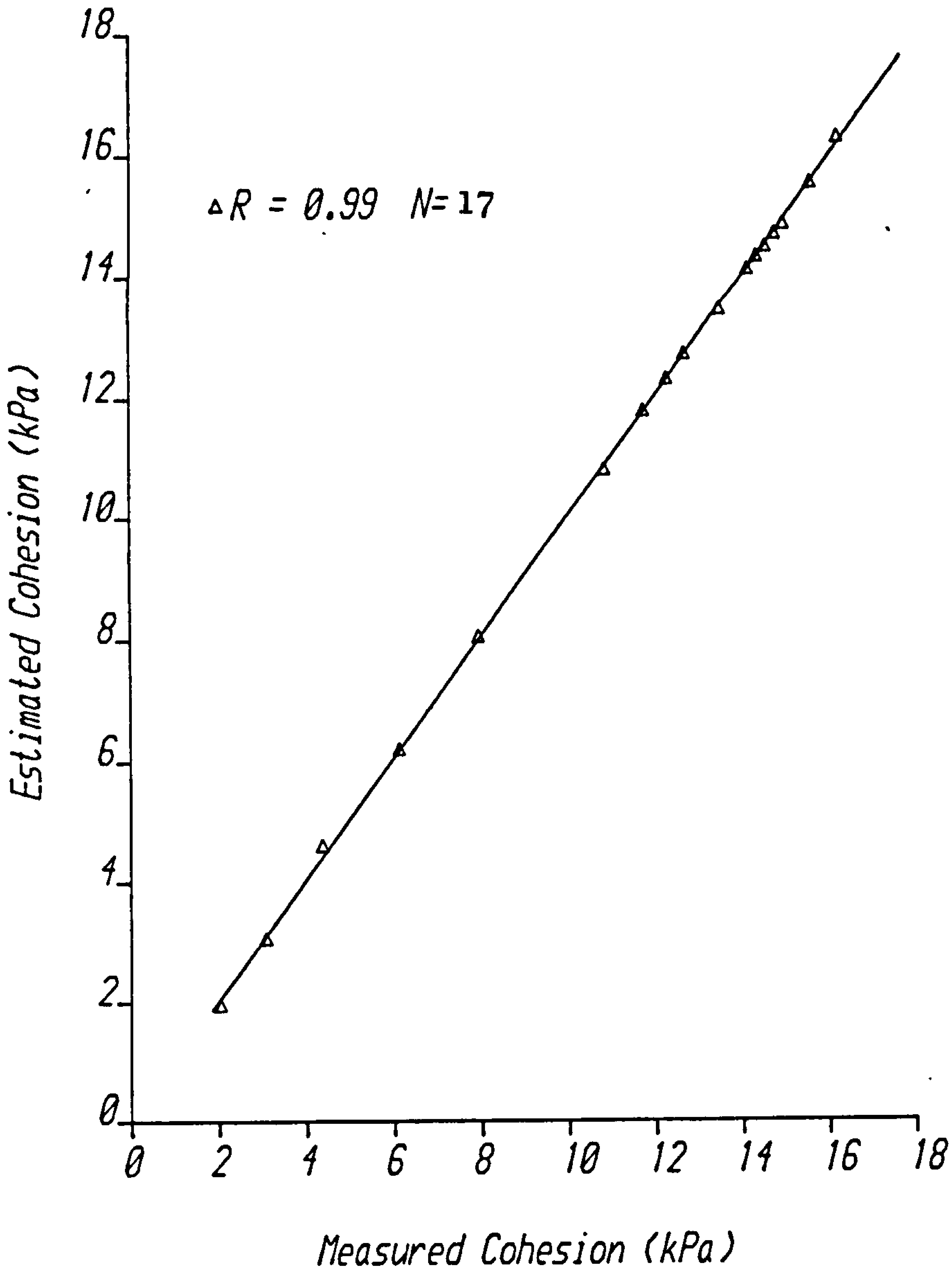
APPENDIX 5.1(b)

DATA FOR THE EFFECT OF ROOT DENSITY ON SOIL COHESION AND FRICTION

	ROOT DENSITY g/cm^3	COHESION kPa	INCREASE IN COHESION kPa	FRICTION tan Ø	INCREASE IN FRICTION tan Ø
	SANDY CLAY LOAM SOIL				
1	0.000	1.96	-	0.58	-
2	0.056	3.10	1.14	0.72	0.14
3	0.125	4.60	2.64	0.72	0.14
4	0.235	6.19	4.23	0.76	0.18
5	0.395	8.03	6.07	0.79	0.21
6	0.748	10.80	8.84	0.87	0.29
7	0.926	11.78	9.82	0.87	0.29
8	1.080	12.30	10.34	0.88	0.30
9	1.147	12.71	10.75	0.88	0.30
10	1.297	13.45	11.49	0.91	0.33
11	1.446	14.13	12.17	0.90	0.32
12	1.539	14.34	12.38	0.90	0.32
13	1.674	14.50	12.54	0.91	0.33
14	1.767	14.71	12.75	0.91	0.33
15	1.811	14.87	12.91	0.92	0.34
16	1.918	15.55	13.59	0.91	0.33
17	2.100	16.29	14.33	0.90	0.32
	CLAY SOIL				
1	0.000	3.58	-	0.117	-
2	0.085	4.90	1.32	0.301	0.184
3	0.170	7.38	3.80	0.322	0.205
4	0.230	8.02	4.44	0.343	0.226
5	0.400	10.49	6.91	0.270	0.153
6	0.700	12.83	9.25	0.254	0.137
7	0.750	12.98	9.40	0.260	0.143
8	1.050	14.24	10.66	0.247	0.130
9	1.900	17.32	13.74	0.213	0.096
10	2.000	17.48	13.90	0.206	0.089
11	2.200	18.51	14.93	0.172	0.055
12	3.000	20.61	17.03	0.161	0.044

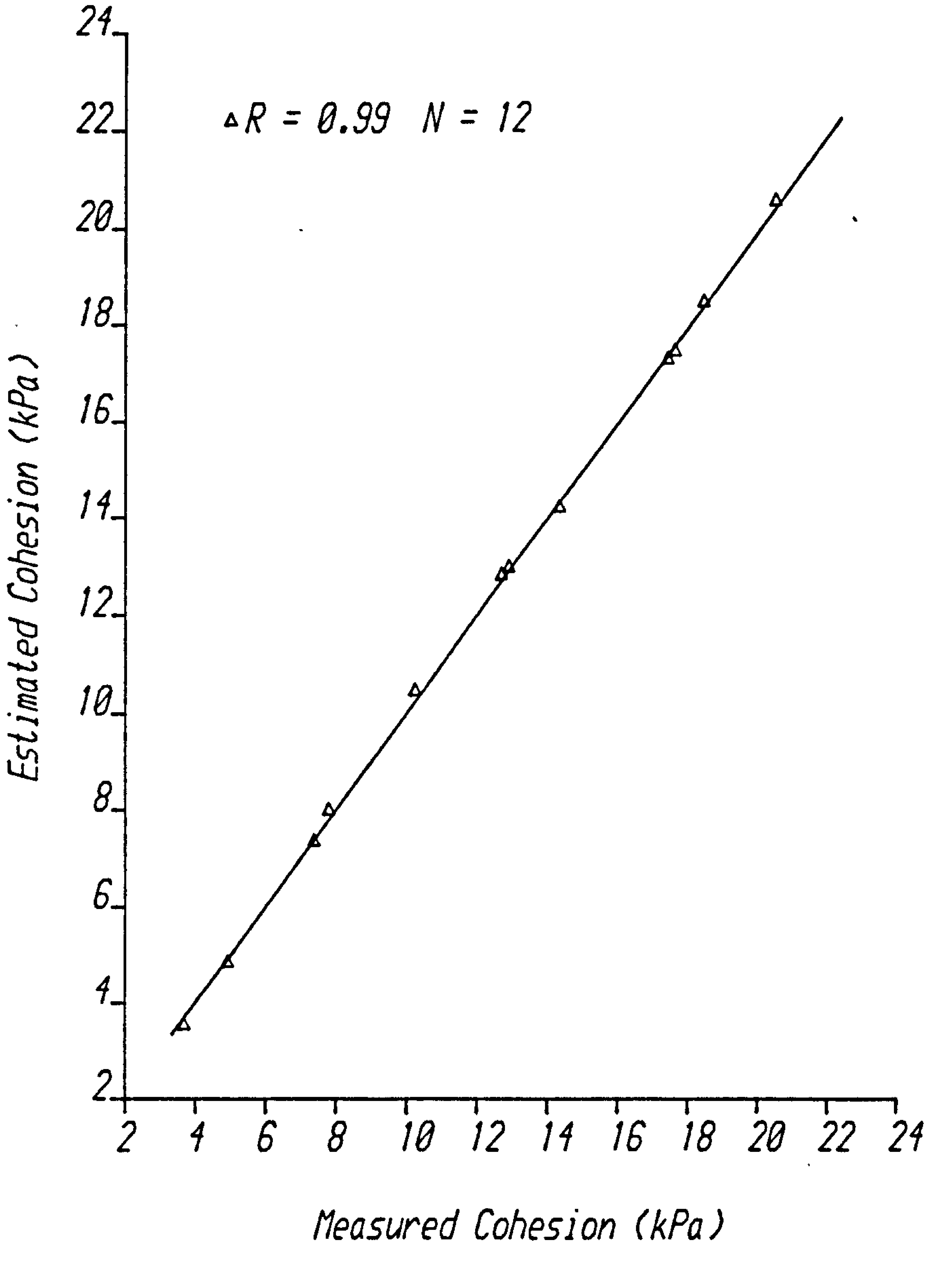
APPENDIX 5.2

CALIBRATION GRAPHS OF THE ESTIMATED VERSUS THE MEASURED/CALCULATED SHEAR STRENGTH PARAMETERS - (A) Sandy clay loam



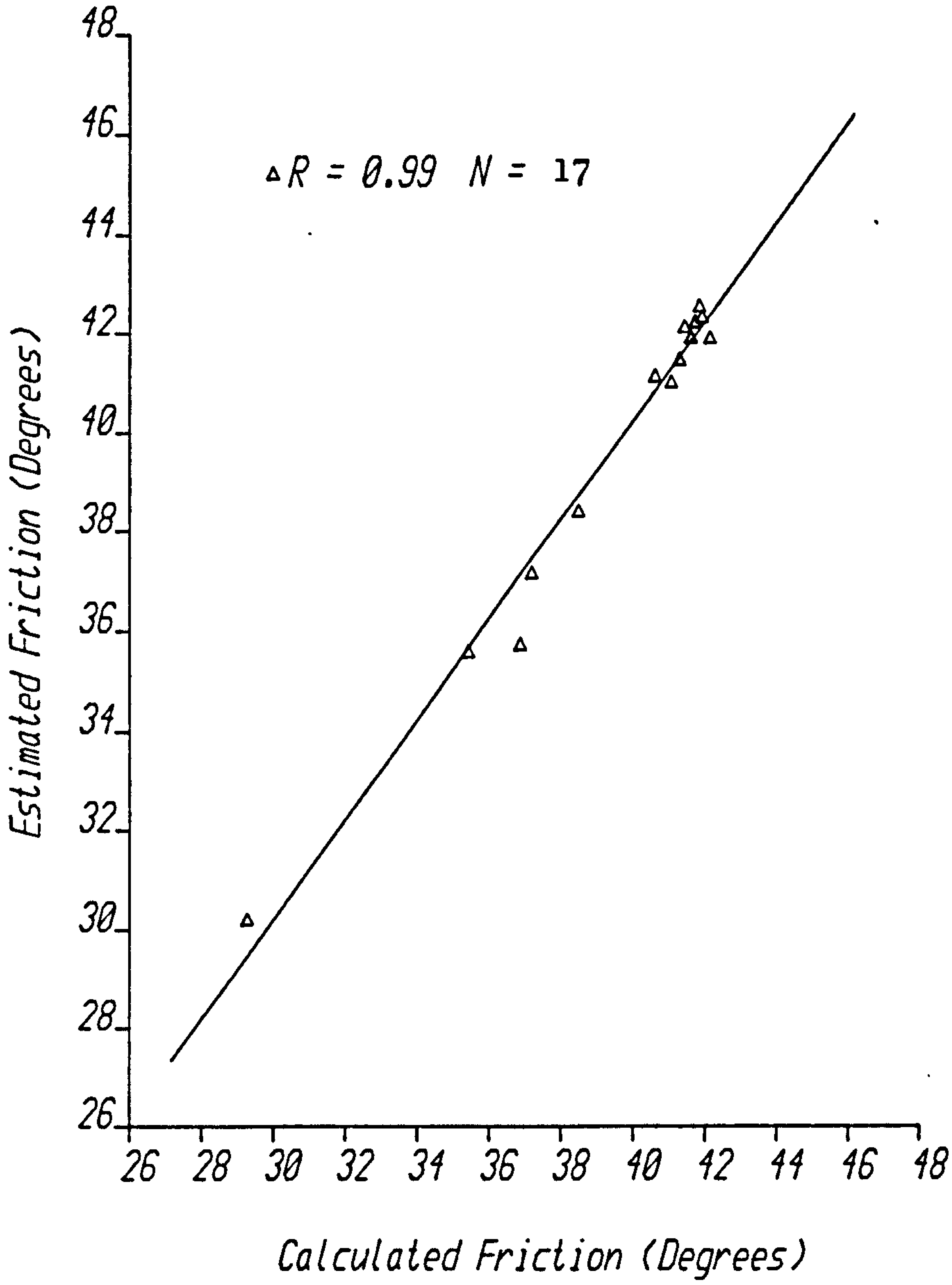
APPENDIX 5.2 (Continued)

CALIBRATION GRAPHS OF THE ESTIMATED VERSUS THE MEASURED/CALCULATED SHEAR STRENGTH PARAMETERS - (B) Clay soil



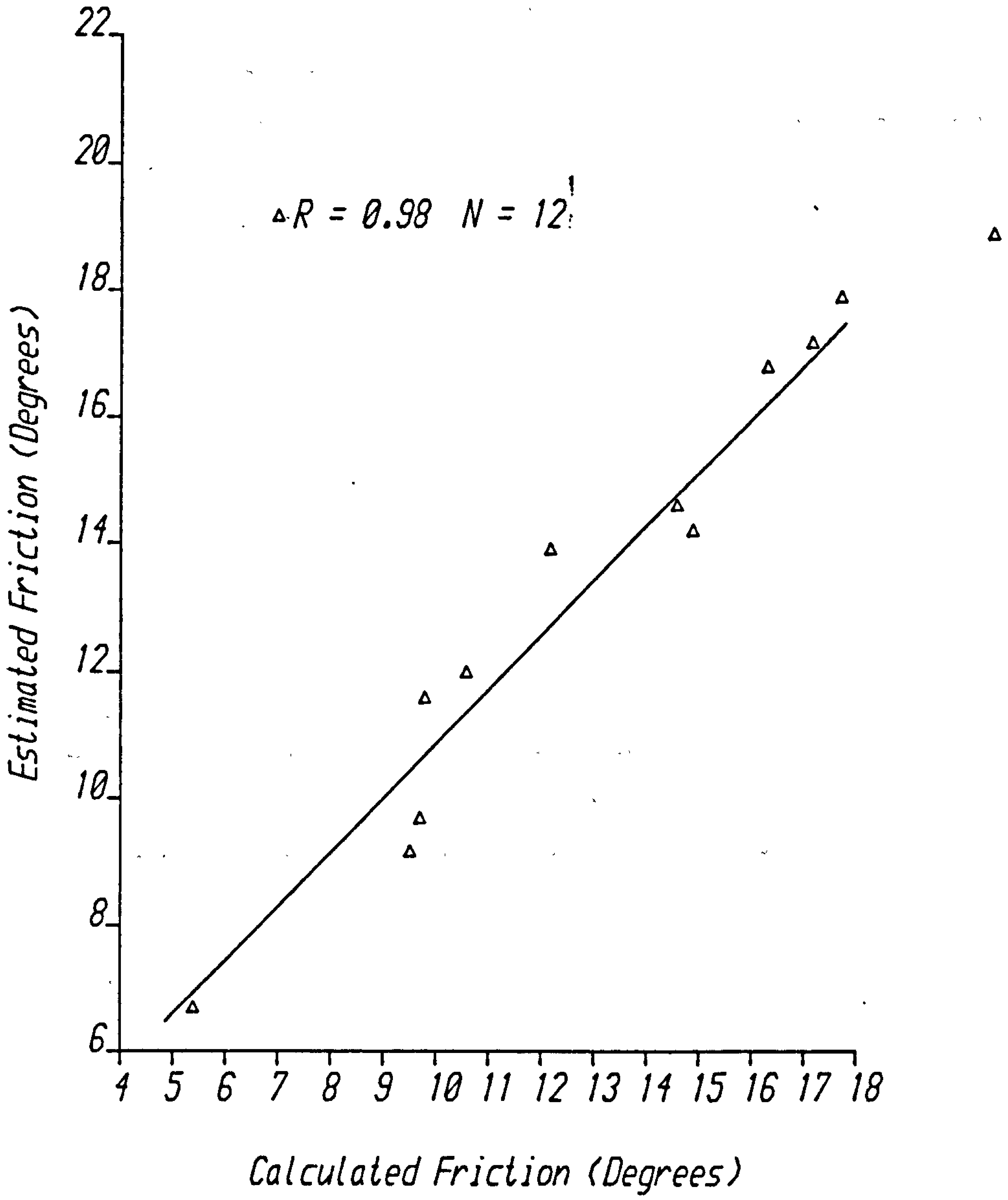
APPENDIX 5.2 (Continued)

CALIBRATION GRAPHS OF THE ESTIMATED VERSUS THE MEASURED/CALCULATED SHEAR STRENGTH PARAMETERS - (C) Sandy clay loam



APPENDIX 5.2 (Continued)

CALIBRATION GRAPHS OF THE ESTIMATED VERSUS THE MEASURED/CALCULATED SHEAR STRENGTH PARAMETERS - (D) Clay soil



APPENDIX 5.2 (Continued)

DATA FOR CALIBRATION GRAPHS OF THE ESTIMATED VERSUS THE MEASURED/ CALCULATED SHEAR STRENGTH PARAMETERS

	ROOT DENSITY g/cm^3	MEASURED COHESION kPa	ESTIMATED COHESION kPa	CALCULATED FRICTION (degrees)	ESTIMATED FRICTION (degrees)
	SANDY CLAY LOAM SOIL				
1	0.000	2.06	1.96	29.29	30.23
2	0.056	3.10	3.10	35.47	35.59
3	0.125	4.40	4.60	36.92	35.73
4	0.235	6.17	6.19	37.24	37.14
5	0.395	8.00	8.03	38.53	38.41
6	0.748	10.90	10.80	40.66	41.16
7	0.926	11.80	11.78	41.11	41.04
8	1.080	12.34	12.30	41.34	41.48
9	1.147	12.75	12.71	41.34	41.49
10	1.297	13.57	13.45	41.48	42.15
11	1.446	14.19	14.13	41.65	41.93
12	1.539	14.40	14.34	41.65	41.94
13	1.674	14.60	14.50	41.77	42.26
14	1.767	14.81	14.71	41.77	42.24
15	1.811	15.01	14.87	41.89	42.57
16	1.918	15.63	15.55	41.96	42.35
17	2.100	16.25	16.29	42.18	41.93
	CLAY SOIL				
1	0.000	3.70	3.58	5.40	6.70
2	0.085	4.94	4.90	16.30	16.80
3	0.170	7.40	7.38	17.70	17.90
4	0.230	7.82	8.02	20.62	18.90
5	0.400	10.28	10.49	17.16	17.18
6	0.700	12.75	12.83	14.90	14.20
7	0.750	12.96	12.98	14.60	14.60
8	1.050	14.40	14.24	12.20	13.90
9	1.900	17.48	17.32	10.60	12.00
10	2.000	17.68	17.48	9.80	11.60
11	2.200	18.51	18.51	9.70	9.70
12	3.000	20.57	20.61	9.51	9.18

APPENDIX 6.1

FLOW HYDRAULICS DATA FOR BARE ROOT DENSITY SAMPLES

ROOT DENSITY (g/cm^3)		FLOW ON BARE SOIL SAMPLES VELOCITY (m/s)	DEPTH (m)	MANNING'S n	REYNOLD'S NUMBER	FROUDE NUMBER	CRITICAL TRACTIVE FORCE(N/m^2)	VANE SHEAR STRENGTH (kPa)
(A)		SANDY CLAY LOAM SOIL (N = 10)						
ROOT-FREE (Control)		0.50000	0.003	0.00756	1495	5.28	0.71	
		0.60000	0.004	0.00763	2392	5.48	0.85	
AVERAGE =		0.55	0.0035	0.0076	1919	5.38	0.827	0.00
1	0.100	0.66000	0.00950	0.01230	6250	3.92		
2		0.74000	0.01000	0.01140	7376	4.28	2.36	0.50
1	0.677	0.56670	0.01000	0.01500	5649	3.28		
2		0.73400	0.01267	0.01347	9270	3.77		
3		0.87583	0.01450	0.01233	12658	4.21		
4		0.99667	0.01617	0.01165	16061	4.53	3.821	1.50
1	0.777	0.52000	0.00900	0.01510	4665	3.17		
2		0.62330	0.01117	0.01460	6938	3.41		
3		0.82000	0.01433	0.01310	11712	3.96		
4		0.99750	0.01750	0.01230	17400	4.36	4.136	2.00
1	0.956	0.57330	0.00983	0.01454	5617	3.34		
2		0.70670	0.01367	0.01470	9629	3.50		
3		0.81920	0.01550	0.01379	12656	3.81		
4		0.88580	0.01767	0.01391	15601	3.85		
5		0.94670	0.02050	0.01437	19344	3.82		
6		1.01100	0.02183	0.01400	21999	3.96		
7		1.01900	0.02350	0.01463	23869	4.87		
8		1.13000	0.02467	0.01362	27787	4.16	5.83	2.50
1	1.075	0.56000	0.01067	0.01572	5956	3.14		
2		0.67000	0.01317	0.01510	8793	3.38		
3		0.78000	0.01550	0.01450	12051	3.62		
4		0.88500	0.01833	0.01430	16169	3.78		
5		0.99500	0.02083	0.01382	20662	3.99		
6		1.08500	0.02300	0.01354	24874	4.14		
7		1.14330	0.02400	0.01322	27350	4.27		
8		1.19167	0.02500	0.01300	29695	4.36	5.91	3.50
1	1.157	0.51000	0.00933	0.01580	4743	3.10		
2		0.62000	0.01167	0.01510	7210	3.32		
3		0.90000	0.01900	0.01440	17045	3.78		
4		1.02670	0.02050	0.01360	20979	4.15		
5		1.11000	0.02400	0.01325	26554	4.14		
6		1.12330	0.02583	0.01410	28921	4.04		
7		1.16670	0.02683	0.01400	31201	4.13		
8		1.20167	0.02750	0.01380	32939	4.19	6.499	4.00
1	1.228	0.53000	0.01000	0.01590	5283	3.07		
2		0.63500	0.01267	0.01555	8019	3.26		
3		0.74000	0.01550	0.01530	11433	3.44		
4		0.86770	0.01817	0.01450	15694	3.72		
5		0.91670	0.01933	0.01430	17662	3.81		
6		1.01830	0.02133	0.01372	21650	4.03		
7		1.07000	0.02267	0.01360	2 178	4.11		
8		1.10000	0.024167	0.01380	26497	4.09		
9		1.14500	0.025167	0.01360	28723	4.17		
10		1.17500	0.026833	0.01386	31426	4.15		
11		1.21500	0.027667	0.01368	33506	4.22		
12		1.21500	0.02800	0.01379	33910	4.20	6.62	4.50

APPENDIX 6.1 (CONTINUED)

ROOT DENSITY (g/cm³)		FLOW ON BARE SOIL SAMPLES VELOCITY (m/s)	DEPTH (m)	MANNING'S n	REYNOLDS NUMBER	FROUDE NUMBER	CRITICAL TRACTIVE FORCE (N/m²)	VANE SHEAR STRENGTH (kPa)
1	1.571	0.64000	0.01333	0.01596	8504	3.21		
2		0.76000	0.01633	0.01539	12371	3.44		
3		0.92000	0.01967	0.01430	18038	3.79		
4		1.01670	0.02267	0.01431	22974	3.91		
5		1.05500	0.02400	0.01433	25238	3.94		
6		1.09330	0.02517	0.01427	27426	3.99		
7		1.12500	0.02633	0.01429	29525	4.01		
8		1.19000	0.02933	0.01452	34789	4.02		
10		1.19000	0.03033	0.01485	35976	3.95		
11		1.19000	0.03083	0.01500	36569	3.92		
12		1.23000	0.03100	0.01457	38006	4.04		
13		1.27000	0.03117	0.01416	39454	4.16		
14		1.27500	0.03133	0.01416	39816	4.17		
15		1.28500	0.03167	0.01415	40560	4.18		
16		1.30000	0.03188	0.01405	41313	4.21		
17		1.32000	0.03200	0.01387	42103	4.27		
18		1.33000	0.03200	0.01386	42422	4.30		
19		1.36000	0.03233	0.01356	43826	4.37	7.64	5.50
1	1.804	0.63000	0.01317	0.01610	8268	3.18		
2		0.75000	0.01617	0.01550	12086	3.41		
3		0.89167	0.02000	0.01500	17776	3.65		
4		0.96830	0.02200	0.01473	21233	3.78		
5		1.05500	0.02500	0.01472	26289	3.86		
6		1.15330	0.02550	0.01365	29314	4.18		
7		1.17670	0.02600	0.01355	30495	4.22		
8		1.20330	0.02683	0.01353	32180	4.25		
9		1.23170	0.02767	0.01349	33971	4.28		
10		1.26330	0.02800	0.01326	35258	4.37		
11		1.27330	0.02817	0.01321	35759	4.39		
12		1.28500	0.02850	0.01319	36504	4.40		
13		1.29660	0.02900	0.01322	37479	4.40		
14		1.31833	0.02967	0.01321	38988	4.43		
15		1.33900	0.03050	0.01324	40707	4.43		
16		1.35000	0.03083	0.01323	41490	4.45		
17		1.36000	0.03100	0.01318	42023	4.47		
18		1.39000	0.03150	0.01304	43643	4.53		
19		1.40500	0.03197	0.01302	44768	4.54		
20		1.41000	0.03217	0.01303	45208	4.55		
21		1.43567	0.03300	0.01302	47223	4.57		
22		1.45000	0.03367	0.01306	48663	4.57	7.96	7.50
(B)		CLAY SOIL	(N = 4)					
1	ROOT-FREE (Control)	0.49000	0.00950	0.01660	4640	2.91		
2		0.64330	0.01133	0.01425	7265	3.50		
3		0.76330	0.01417	0.01393	10779	3.71	3.35	1.50
1	0.164	0.44000	0.00900	0.01786	3947	2.68		
2		0.60000	0.01100	0.01498	6579	3.31		
3		0.71667	0.01410	0.01479	10072	3.49		
4		0.86670	0.01483	0.01265	12811	4.12		
5		0.98330	0.01617	0.01181	15845	4.47		
6		1.07000	0.01750	0.01144	18664	4.68	4.14	2.00
1	0.358	0.43500	0.00900	0.01807	3902	2.65		
2		0.49700	0.01100	0.01808	5449	2.74		
3		0.57000	0.01233	0.01700	7005	2.97		
4		0.74167	0.01467	0.01470	10845	3.54		
5		0.82830	0.01567	0.01370	12937	3.83		
6		0.88167	0.01617	0.01320	14210	4.01		
7		0.98667	0.01767	0.01250	17378	4.29		
8		1.01667	0.01967	0.01300	19933	4.19		
9		1.07167	0.02083	0.01280	22250	4.29		
10		1.09330	0.02150	0.01280	23430	4.31		
11		1.10167	0.02267	0.01320	24894	4.23		
12		1.13167	0.02350	0.01320	26508	4.27		
13		1.13833	0.02433	0.01340	27606	4.22		
14		1.14500	0.02500	0.01360	28532	4.19		
15		1.15167	0.02567	0.01370	29467	4.16		
16		1.15833	0.02667	0.01399	30615	4.10		
17		1.17167	0.02700	0.01395	31532	4.12	6.38	3.50

APPENDIX 6.1 (CONTINUED)

ROOT DENSITY (g/cm^3)		FLOW ON BARE SOIL SAMPLES						VANE SHEAR STRENGTH (kPa)
		VELOCITY (m/s)	DEPTH (m)	MANNING'S n	REYNOLD'S NUMBER	FROUDE NUMBER	CRITICAL TRACTIVE FORCE(N/m^2)	
1	0.600	0.43000	0.00950	0.01895	4072	2.55	7.51	4.5
2		0.51000	0.01200	0.01867	6100	2.69		
3		0.69000	0.01500	0.01600	10316	3.26		
4		0.88000	0.01700	0.01360	14911	3.90		
5		0.96700	0.01900	0.01340	18313	4.06		
6		1.01000	0.02000	0.01330	20134	4.13		
7		1.03000	0.02090	0.01340	21457	4.12		
8		1.05670	0.02100	0.01310	22119	4.22		
9		1.07000	0.02150	0.01310	22936	4.22		
10		1.08500	0.02300	0.01350	24874	4.14		
11		1.09500	0.02540	0.01430	27723	3.97		
12		1.09900	0.02700	0.01490	29577	3.87		
13		1.10000	0.02810	0.01530	30810	3.79		
14		1.10670	0.02883	0.01540	31803	3.77		
15		1.11000	0.02939	0.01560	32517	3.74		
16		1.15000	0.03030	0.01535	33675	3.70		
17		1.19000	0.03083	0.01500	34387	3.69		
18		1.20000	0.03184	0.01510	35099	3.65		
19		1.28000	0.03178	0.01424	35732	3.66		

APPENDIX 6.2

FLOW HYDRAULICS DATA FOR VEGETATED SAMPLES

	INCOMING FLOW		FLOW IN VEGETATED SAMPLES							
	VELOCITY (m/s)	DEPTH (m)	VELOCITY (m/s)	% INCREASE	DEPTH (m)	% INCREASE	MANNING'S n	REYNOLD'S NUMBER	FROUDE NUMBER	TRACTIVE FORCE N/m^2
				Vegetation Density = 80 Stands/m^2						
1	0.67	0.010	0.28667	57	0.0130	30	0.0330	3715	1.450	3.10
2	0.72	0.012	0.295	59	0.02033	69	0.0459	6019	1.197	4.80
3	0.85	0.015	0.37	56	0.032	113	0.0495	11759	1.196	7.60
4	0.92	0.018	0.43	53	0.041	128	0.0500	17374	1.228	9.70
5	1.01	0.022	0.49	51	0.0528	140	0.0522	25787	1.233	12.50
6	1.05	0.025	0.60	43	0.0660	164	0.0490	39472	1.351	15.60
7	1.10	0.028	0.85	22	0.0820	193	0.0400	69472	1.714	19.40
8	1.15	0.0295	0.97	18	0.0850	188	0.0360	82182	1.924	20.10
				Vegetation Density = 100 stands/m^2						
1	0.67	0.010	0.265	60	0.0140	40	0.0398	3698	1.295	3.31
2	0.72	0.012	0.2832	61	0.0210	75	0.0488	5928	1.130	5.00
3	0.85	0.015	0.3500	59	0.0335	123	0.0539	11687	1.106	7.92
4	0.92	0.018	0.4050	56	0.0420	133	0.0542	16955	1.143	9.93
5	1.01	0.022	0.4700	53	0.0530	141	0.0545	24829	1.181	12.53
6	1.05	0.025	0.5400	49	0.0680	172	0.0560	36601	1.198	16.10
7	1.10	0.028	0.7800	29	0.0880	214	0.0460	64417	1.521	20.80
				Vegetation Density = 150 stands/m^2						
1	0.67	0.010	0.1800	73	0.01583	58	0.06363	2840	0.827	3.74
2	0.72	0.012	0.2250	69	0.02367	97	0.06660	5308	0.846	5.60
3	0.85	0.015	0.2633	69	0.03533	136	0.07430	9270	0.810	8.35
4	0.92	0.018	0.3000	69	0.04367	143	0.07510	13058	0.830	10.32
5	1.01	0.022	0.3400	66	0.05433	147	0.07664	18412	0.844	12.84
6	1.05	0.025	0.4100	61	0.07100	184	0.07597	29016	0.890	16.80
				Vegetation Density = 180 stands/m^2						
1	0.67	0.010	0.14667	78	0.01700	70	0.08200	2485	0.651	4.02
2	0.72	0.012	0.19000	74	0.02567	114	0.0832-	4861	0.686	6.10
3	0.85	0.015	0.23000	73	0.03600	140	0.08611	8253	0.701	8.51
4	0.92	0.018	0.28000	70	0.04900	172	0.08688	13675	0.732	11.60
5	1.01	0.022	0.32000	68	0.06100	177	0.08797	19443	0.750	14.42
6	1.05	0.025	0.38000	64	0.07233	189	0.08299	27395	0.817	17.10
				Vegetation Density = 200 stands/m^2						
1	0.67	0.010	0.14330	79	0.0200	100	0.0930	2857	0.586	4.73
2	0.72	0.012	0.18667	74	0.0300	150	0.0940	5582	0.0623	7.10
3	0.85	0.015	0.22670	73	0.0420	180	0.0968	9490	0.640	9.93
4	0.92	0.018	0.25667	72	0.0530	194	0.0999	13559	0.645	12.53
5	1.01	0.022	0.2920	71	0.0650	195	0.1010	18918	0.662	15.40
6	1.05	0.025	0.3500	67	0.0770	208	0.0940	26863	0.729	18.20

APPENDIX 7.1, JANBU'S (1954) GRAPHS FOR ESTIMATING STABILITY NUMBERS

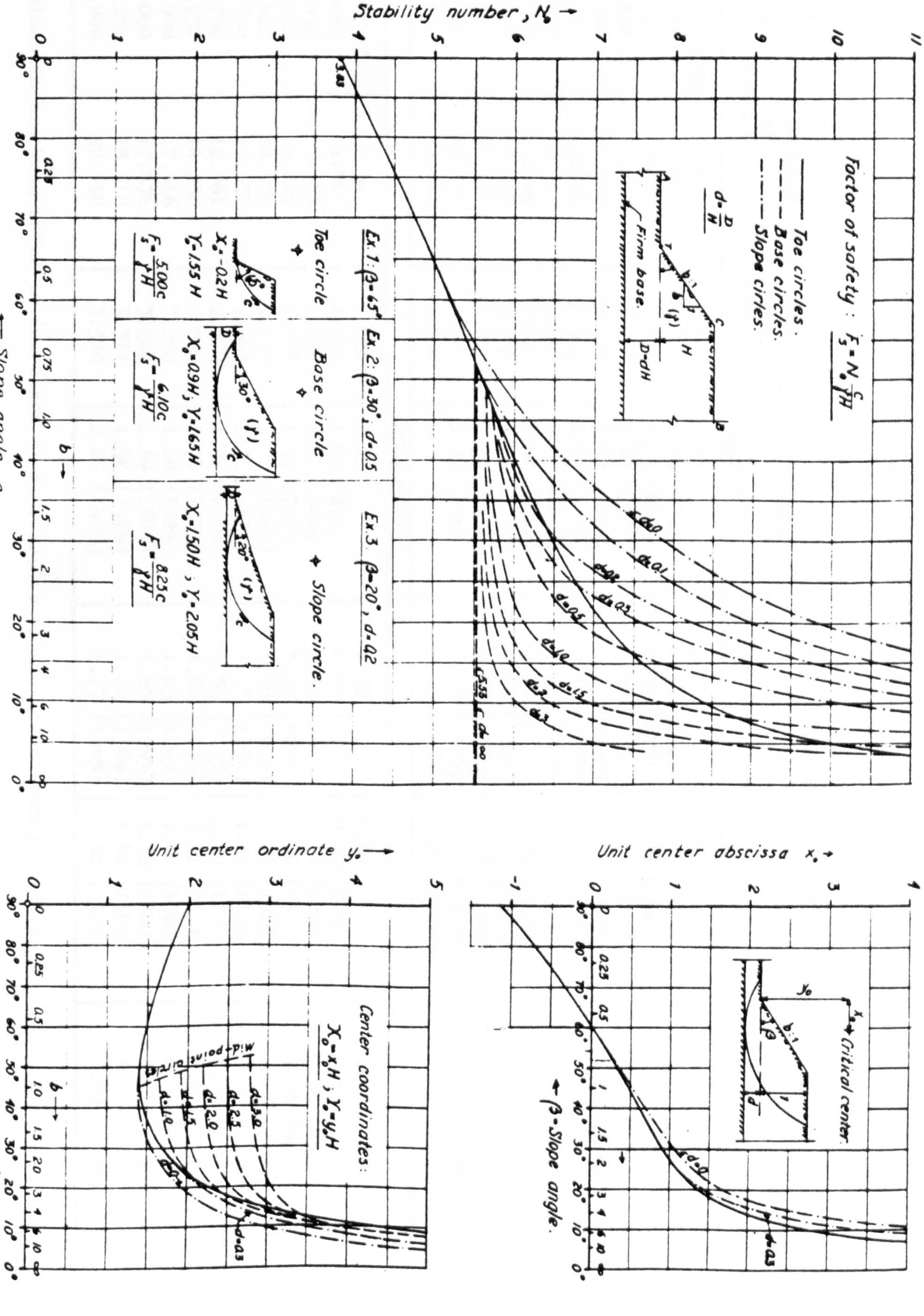


FIG.2-1. STABILITY NUMBER AND CRITICAL CENTER COORDINATES FOR SIMPLE SLOPES WHEN ϕ=o.

APPENDIX 7.2 FACTORS OF SAFETY (Fs) OF CHANNEL BANK SLOPES WITH DIFFERENT ROOT DENSITIES

ROOT DENSITY g/cm^3	UNDRAINED COHESION (Cu) kPa	BULK DENSITY g/cm^3	CALCULATED FACTORS OF SAFETY (Fs)			
			30^o BANKS	40^o BANKS	53^o BANKS	ASSUMED VERTICAL BANKS
BANK HEIGHT = 1.5m						
ROOT-FREE	3.58	1.540	1.23	1.08	0.90	0.61
0.085	4.90	1.663	1.56 (27%)	1.36 (26%)	1.14 (26%)	0.77 (26%)
0.070	7.383	1.726	2.27 (85%)	1.98 (83%)	1.66 (84%)	1.11 (82%)
0.230	8.022	1.934	2.20 (79%)	1.92 (78%)	1.61 (78%)	1.10 (80%)
0.400	10.490	2.173	2.56 (108%)	2.23 (106%)	1.87 (107%)	1.26 (107%)
0.700	12.833	2.543	2.68 (118%)	2.33 (116%)	1.96 (118%)	1.31 (115%)
0.750	12.981	2.573	2.68 (118%)	2.33 (116%)	1.96 (118%)	1.31 (115%)
1.050	14.236	2.808	2.69 (119%)	2.34 (117%)	1.97 (119%)	1.32 (116%)
1.900	17.316	3.232	2.84 (131%)	2.48 (130%)	2.02 (124%)	1.39 (128%)
2.000	17.476	3.262	2.84 (131%)	2.48 (130%)	2.02 (124%)	1.39 (128%)
2.200	18.510	3.311	2.97 (141%)	2.59 (140%)	2.17 (141%)	1.46 (139%)
3.00	20.610	3.590	3.04 (147%)	2.65 (145%)	2.23 (148%)	1.50 (146%)
BANK HEIGHT - 2.25m						
ROOT-FREE	3.58	1.540	0.82	0.72	0.60	0.40
0.085	4.90	1.663	1.04 (27%)	0.91 (28%)	0.76 (27%)	0.51 (28%)
0.070	7.383	1.726	1.51 (84%)	1.32 (83%)	1.11 (85%)	0.74 (85%)
0.230	8.022	1.934	1.47 (79%)	1.28 (87%)	1.10 (83%)	0.72 (80%)
0.400	10.490	2.173	1.71 (109%)	1.49 (107%)	1.25 (108%)	0.84 (110%)
0.700	12.833	2.543	1.78 (117%)	1.55 (115%)	1.30 (117%)	0.88 (120%)
0.750	12.981	2.573	1.78 (117%)	1.55 (115%)	1.30 (117%)	0.88 (120%)
1.050	14.236	2.808	1.79 (118%)	1.56 (117%)	1.31 (118%)	0.88 (120%)
1.900	17.316	3.232	1.89 (130%)	1.65 (129%)	1.38 (130%)	0.93 (133%)
2.000	17.476	3.262	1.89 (130%)	1.65 (129%)	1.38 (130%)	0.93 (133%)
2.200	18.510	3.311	1.98 (141%)	1.72 (139%)	1.44 (140%)	0.97 (143%)
3.000	20.610	3.590	2.03 (148%)	1.77 (146%)	1.48 (147%)	0.99 (148%)

Values in brackets refer to increases of Fs relative to root-free (bare) conditions